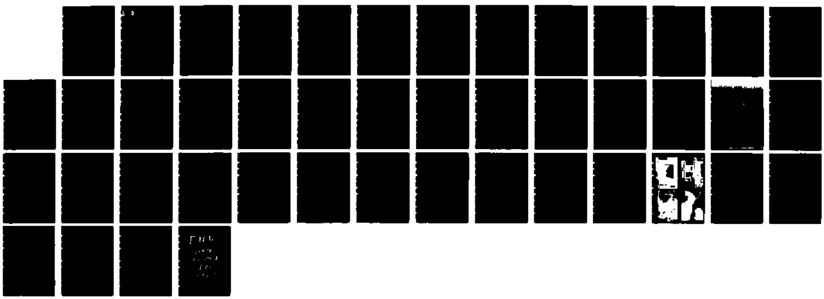
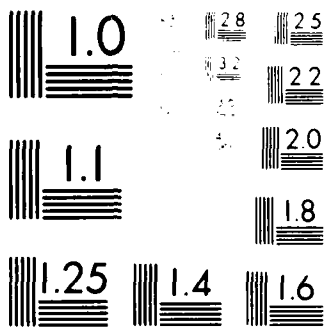
AD-A186 136 LOW NOISE CATALYTIC IGNITION IC ENGINE(U) PFELLERLE (WILLIAM C) ASSOCIATES MIDDLETOWN NJ 1987 DAAK70-86-C-0110 1/1

UNCLASSIFIED F/G 21/2 NL





1.0
2.8
2.5
3.2
2.2
2.0
1.1
1.8
1.25
1.4
1.6

LOW NOISE CATALYTIC IGNITION I.C. ENGINE
FINAL TECHNICAL REPORT
ITEM NO 0001AC
CONTRACT NO. DAAK70-86-C-0110

Prepared by: William C. Pfefferle Associates

ABSTRACT

A prototype catalytic ignition internal combustion engine using diesel fuel was evaluated and experimentally tested for potential beneficial effects in reducing engine noise. Experimental results produced a total sound pressure improvement in the 4 - 5 dB range. Noise reductions were even larger in the speech frequency and high human sensitivity ranges. Literature research and theoretical advancements indicate the potential for a larger noise reduction as well as a confirmation that the reduction, resulting from a reduction in combustion noise, would be additive with most other conventional sound improvement technologies. Independent of noise reduction potential, the catalytic ignition technology also shows strong potential to produce significant improvements in fuel economy, power, cold start capabilities, pollutant emissions and multifuel capability (both in terms of improved fuel quality insensitivity and an ability to utilize low or zero cetane fuels).

Early prototypes of the catalytic ignition engine have been fabricated by modifying an existing diesel engine, and it is believed that commercial production of a fully-developed catalytic ignition engine would involve relatively little redesign and retooling from existing diesel production. Cost of a commercial catalytic engine is estimated to be low ($10 to $40 per cylinder above existing diesel engines) and a retrofit capability has been demonstrated.

IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM AND OPPORTUNITY

Engine noise can be characterized as deriving from two primary sources: mechanical noise and combustion noise. For non-turbocharged diesel engines, combustion noise generally predominates whereas for the gasoline engine mechanical noise is usually more significant. In diesel engine generator set usage (among other military diesels), significantly reducing the combustion noise enables more effective overall noise control. This is especially true since much of the mechanical noise such as piston slap and even timing gear noise have a combustion induced component [1]. With much of existing technology focused on enclosures and methods for reducing mechanical noise, there is substantial potential to add to the effectiveness of existing technologies through methods which would reduce combustion noise.

William C. Pfefferle Associates (WCP) has developed a proprietary catalytically-enhanced modification of a diesel engine which has the potential for a number of promising features, including a lowered noise level. This catalytic diesel has the potential to significantly reduce engine noise, doing so in a way that still leaves room for other conventional noise improvement technologies to add their full reduction. Furthermore, the noise improvement appears concentrated in the

speech frequency and high human sensitivity ranges (which overlap), producing an even higher effective reduction in audible detection and command interference performance.

Regarding prospective weight, volume and performance characteristics, the catalytic ignition engine is expected to produce improved fuel economy and improved power compared to an unmodified diesel. The increased power component would actually permit a smaller, lighter engine to be able to meet a specified power requirement (the modification itself involves insignificant change in the weight of the engine). Other potential benefits of this engine modification include lower soot emissions, reduced exhaust emission temperatures, improved cold starting and the ability to burn gasoline, methanol and ethanol as well as diesel fuel. Furthermore, catalytic ignition is highly synergistic with most aspects of advanced technology diesel engines. Costs are estimated in the $10 to $40 range per cylinder (above the cost of a diesel engine), and other diesel technologies inherent in advanced technology diesels would be compatible with catalytic ignition.

In operation our catalytic engine resembles a spark-ignited diesel, but with important differences such as a multipoint surface ignition by a catalyst, the ability to burn very lean fuel/air mixtures, and a design with excellent potential durability. In concept we can take the low maintenance, durability, high-compression, unthrottled operation of the diesel engine and combine it with the benefits of closer to constant-volume combustion and easier ignition. We have the potential with this technology to optimize compression ratio for efficiency (because we no longer need quite as high a compression for ignition purposes). We believe we can also systematically affect the shape of the combustion curve if such should prove important in achieving the maximum reduction in noise. The result is a hybrid engine which combines some of the best features of the diesel engine and the spark-ignited Otto cycle gasoline engine, further adding to these the emission and multifuel advantages of an active in-cylinder catalyst.

DIESEL ENGINE COMBUSTION AND NOISE

Diesel engine combustion noise is inherent to the nature of the diesel combustion process. In diesels, fuel is injected into hot, high pressure air and autoignition of the fuel results from heating of the injected fuel by the high temperature air. Typically the compression ratio of the engine must be high enough to raise the air temperature well above the autoignition temperature of the fuel in order to keep the ignition delay short.

As is now well understood, diesel combustion occurs in three stages as postulated by Ricardo in 1930 [2]:

1. First, in the ignition delay period, fuel droplets are heated and fuel vaporization occurs. As noted by Taylor [3], the ignition lag typically is long enough so that a considerable quantity of fuel is vaporized. This ignition lag depends upon a number of factors, including air temperature and pressure, fuel

cetane level, spray droplet size, and the temperature of the combustion chamber walls on which the fuel impinges. Moreover, because autoignition depends upon heating of the fuel spray by the hot compressed air, ignition lag is very much influenced by engine turbulence and ignition timing is therefore variable from cycle to cycle. Further, the randomness of the turbulence also means that ignition occurs at different points in the combustion chamber in each cycle. This has noise implications as will be discussed later.

2. Following ignition, there is a period of rapid combustion which consumes nearly all the fuel which has vaporized and mixed with air during the initial lag period. The rapid combustion results in a pressure wave typically exhibiting high frequency oscillations (with frequencies in the audible range) thought to result from the collisions of the pressure waves originating from the multiple, relatively randomly-located ignition points. As noted by various researchers, eg Hickling et al [4] and Dykstra [5], it is generally believed that a rapid rate of pressure rise in the cylinder generates the frequencies responsible for diesel noise. This spontaneous ignition of prevaporized fuel is basically the same as autoignition (knocking) in a spark-ignited engine, with one important distinction being that the diesel controls the timing of autoignition through fuel injection timing so that ideally at least it occurs close to top dead center. The resulting high frequency oscillations are believed to be responsible for the typical diesel clatter.

3. In the third combustion stage, fuel droplets ignited by the initial rapid combustion continue to burn until consumed or quenched by the expansion and exhaust strokes. This diffusion flame droplet combustion continues for a significant duration after the rapid combustion period and may contribute to the observed oscillations of in cylinder pressure responsible for noise.

A-125

DIESEL ENGINE NOISE

Diesel engine noise is dominated by combustion noise, in comparison to the spark-ignited gasoline engine where combustion noise is lower and mechanical noise dominates [6]. Direct injection diesel engines emit on the order of magnitude of 15 dB more total sound pressure than gasoline carburated spark-ignited engines [7]. The primary components of this increased noise are combustion noise [5] and piston slap [8] (which itself is related to the combustion noise and the high compression of the diesel). Because the catalytic ignition engine transforms the nature of combustion in the engine, its impact on noise is through its effect on this primary source of diesel engine noise.

The specific causes of the diesel's increased combustion noise are reported by numerous researchers to be related to the increased peak pressure, the rate of pressure rise and the local change in the rate of pressure rise (the second derivative of pressure)[4,9,10,11]. Other causes are reported to include the local pressure fluctuations ("ripples") in the combustion pressure wave and major cycle to cycle variations between

pressure waves [9,12,13].

The major part of diesel combustion sound energy intensity occurs at the relatively low frequencies corresponding to the repetition rate of the combustion process (in the range of 10 to 40 Hz depending on engine speed). Fortunately, very little of this energy escapes the engine as noise because engine structures do not radiate effectively at frequencies below approximately 200 Hz [4].

Diesel combustion normally excites high frequency resonances primarily as harmonics. However, as noted by Hickling et. al. [4], frequencies higher than 4-5 kiloHertz, like the very low frequencies, are not effectively radiated by the engine structure. Thus the major portion of detectable combustion noise is in the range of about 200 to 5000 Hz, and this band is further reduced by a number of researchers to focus around 800 - 3000 Hz [4,9]. In fact, these bands contain the frequencies most detectable by the human ear (centered around 1000 to 4000 Hz), and reductions in noise emissions in these frequencies will have the greatest relative impact on human hearing.

CATALYTIC IGNITION ENGINE COMBUSTION

More research needs to be done to fully understand the mechanisms involved in catalytic ignition engine combustion, but we believe the following description summarizes the effects involved.

Two Primary Phases

The in-cylinder catalyst acts to promote combustion in two phases:

1. Catalytic Surface Oxidation: Fuel is oxidized by the contact of fuel and air with the surface of an active ignition catalyst system resident in the combustion chamber of the engine. These reactions rapidly heat up the catalyst itself and create a hot boundary layer at the surface as well as creating radical species. The result from an appropriately active catalyst is a hot ignition source.

2. Ignition of rapid gas-phase combustion: Contact of hot fuel and air with the hot boundary layer (aided by the radicals) or the catalyst surface is sufficient to ignite the gas phase fuel/air mixture.

The catalyst will rapidly burn fuel which is at the surface (droplets will be vaporized by the hot boundary layer on the surface). In the process, a significant amount of energy is released, which is believed sufficient to burn or vaporize and burn the remainder of the larger droplets. In comparison with normal autoignition flame propagation, catalytic ignition will ignite fuel at lower air temperatures and can combust leaner premixed fuel-air mixtures. Note that the lower required compression temperature also enables the catalytic ignition engine to operate at a lower compression ratio than would be

required for effective diesel ignition. A related benefit is that combustion can proceed more completely with catalytic ignition.

Discussion

Although surface catalytic reactions are very important to the operation of our catalytic engine, the primary mechanism is the consequent ignition of gas phase reactions. Catalytic surface oxidation reactions have the virtue of occurring at very low temperatures (even below ambient temperature with some active catalysts), but they are also mass transfer-limited (the fuel and air must actually get to the catalyst surface). For any heterogeneous catalytic process, reaction rate on a surface cannot occur at a steady state rate greater than that at which reactants (in this case, fuel and air) can be transported to the surface or at which products can be transported away. This limitation, first recognized by Wagner [14], means that beyond a certain value the reaction rate cannot be increased simply by increasing catalytic activity. Of crucial importance is the fact that mass transfer coefficients are so low that catalytic surface reactors are many times the size of a flame combustor. Catalysts, however, can be used to promote flame combustion even outside the usual flammable limits [15-17], with the implication that a suitably configured catalytic ignitor can ignite a fuel/air mixture which is very lean.

Since surface catalysis itself is insufficiently fast to burn the bulk of the fuel in an engine in a relatively rapid period, gas phase combustion is needed. The catalytic ignition engine depends upon the fact, as demonstrated by the gas turbine catalytically-stabilized combustor (invented by Dr. William Pfefferle), that catalysts can be used in a two-phase process to promote very rapid gas phase combustion with fuel-air mixtures well below the normal lean flammability limit.

The theory behind the operation of the catalytically stabilized combustor is not yet fully understood (despite the work of dozens of investigators over the past 15 years). It appears that the active catalytic hot surface, in contact with local fuel/air mixtures, ignites surface combustion, resulting in energy liberation and the formation of large numbers of active radical species (notably OH and O), which help to ignite the fuel/air mixture some distance from the catalyst surface. Thus surface-induced catalytic combustion both provides a hot ignition source and appears to give rise to radical species which diffuse away from the surface and speed ignition of combustion in the gas phase [18, 19].

Wide-Area Ignition

Our catalytic engine also produces more rapid combustion for another reason: by placing the catalyst across a wide surface area in the combustion chamber, we are providing for what we term wide-area ignition in the chamber, with the result that flame propagation distances are short and thus combustion proceeds more quickly. This leads to more of the energy being released within a shorter period of time and a combustion pressure trace closer to constant-volume combustion

than diesel engines would normally be able to achieve. The result is the potential for higher thermodynamic efficiency than is now achievable in diesel engines. As noted by Muranaka et al, deviation of an engine from constant volume combustion results a loss in thermodynamic efficiency which becomes larger as the combustion duration is lengthened [20]. The capability of a catalytic ignition engine to approach constant volume combustion thus has positive implications for fuel economy and power per stroke, particularly for higher speed engines. In a redesigned engine, higher speed operation is feasible because combustion speed is an important limiting factor to choosing peak diesel engine speed.

In addition, it is believed that because combustion is less random and the combustion propagates away from the piston surface in a direction normal to the surface, engine vibration and random oscillations are reduced, producing a smoother combustion pressure history. Finally, the reduction in randomness in individual combustion cycles leads to a more repetitive combustion cycles, reducing cycle to cycle variations.

The more rapid combustion and faster energy release can lead to higher peak pressures in the combustion chamber, which may lead to obvious structural challenges. At the same time, the improved cycle to cycle peak pressure consistency and the reduction in in-cycle random oscillations reduce structural requirements. We cannot yet determine whether the net effect will be an increase or a decrease in overall structural strain, although we do forsee the need for stronger bearings if engine compression is not purposefully reduced.

Other Catalytic Ignition Effects

Catalytic ignition has a number of other in terms of ignition. The ability of the catalyst system to oxidize fuel at a lowered temperature adds the following capabilities (not necessarily having a noise impact):

1. Lower-compression ratios: Without a need for high compression to achieve autoignition within a reasonable ignition delay, a catalytic ignition engine could operate at a compression ratio designed to maximize fuel economy.

2. Improved cold-starting: It is believed a catalytic ignition system could more easily achieve ignition at low ambient temperatures, compared to autoignition. Cetane rating is essentially irrelevant to effective catalytic ignition.

3. Improved fuel quality insensitivity: Also related to the cetane independence of catalytic ignition, we expect a given catalytic ignition configuration to be able to combust a wider range of fuels than autoignition in a comparable engine.

4. Multifuel capability: Again related to cetane independence, catalytic ignition systems are expected to be designable to burn a wide variety of fuels. For example, the catalysts we are working with now will more easily ignite methanol than even diesel fuel.

It is believed that operation with low cetane fuels such as methanol, ethanol, and high aromatic content diesel will permit use of a lower compression ratio in a catalytic engine and the resulting lower peak pressure would lead to even lower noise levels. Our experience with the gas turbine catalytic combustor has shown that such fuels ignite in the presence of a catalyst at lower temperatures than diesel fuels and thus should require a lower compression ratio. In general, the higher the temperature for autoignition of a fuel the lower the temperature for reaction on the surface of an active catalyst (e.g. although the autoignition temperature of methanol is some 300 K higher than that of typical diesel fuels, methanol unlike diesel fuel will burn in the presence of an active catalyst at temperatures below 100 C).

5. Improved emissions: It is expected that fuel will be more completely burned with fully effective catalytic ignition.

Prior Research

While to our knowledge we know of no researcher, present or past, who has worked with our approach to in-cylinder catalytic ignition, there has been prior work to achieve some version of catalytic ignition. This is summarized in our Appendix A.

EFFECT OF CATALYTIC IGNITION ENGINE UPON NOISE

Our experimental results tangibly demonstrate that a catalytic ignition engine can have consistently lower noise output than an equivalent diesel engine. While additional studies would need to be done to better evaluate the reasons the catalytic ignition engine produces lowered combustion noise, the following effects could be important factors.

1. Smoother rate of pressure change: It appears that the rate at which combustion pressure changes in the catalytic engine may be less sharp than in our baseline engine. A smoother rate of change is believed to lead to lowered levels of high frequency oscillations in the audible range and an increased shift in the mix of sound energy towards lower frequencies for which the engine structure is a less effective radiator (and which are less audible in any case).

2. Improved cycle to cycle consistency: Strahle [12,13] has published papers ascribing a significant component of the diesel engine's increased noise vs the gasoline engine to its cycle to cycle variations in compression history and in peak pressure. Strahle reported that even small variations can dominate oscillations in the frequency range of interest to diesel engine noise, and he concluded that these variations are responsible for a substantial amount of noise radiated from the engine. While there has been no work to our knowledge following up on Strahle's findings, it is possible that by reducing these cycle to cycle variations, the catalytic ignition engine may reduce noise.

3. Reduced high frequency oscillations within the combustion cycle (independent of smoother changes in the rate of pressure change): The pressure release of the basic combustion cycle and its lower harmonics are at frequencies which the engine

structure does not effectively radiate, as noted above. However, high frequency oscillations in the pressure wave are emitted in the 500 to 5000 Hz range, and are more likely to escape the structure. Furthermore, these oscillations are in a frequency range which is more audible to the human ear. If it directly reduces the oscillations (evidenced indirectly by a reduction in ripples in the pressure wave), the catalytic engine could reduce noise in a frequency range especially important to human hearing.

4. Shift in sound energy away from the audible range: The increase rate of energy release in a catalytic ignition engine and the higher peak pressures associated with constant volume combustion can be viewed as sources of increased noise. However, as noted above, the combustion frequency (30Hz at 3600RPM) is in the range which the engine structure radiates poorly. Thus, if fewer high frequency harmonics are generated, less external noise will be produced. Our experimental results support the conclusion that higher peak pressures and a high heat release rate approaching Otto cycle performance need not be accompanied by increased sound pressure.

EARLIER PROTOTYPE CATALYTIC ENGINES

First Prototype Engine

WCP's first catalytic ignition prototype (operated prior to the start of this contract) produced the following:

1. Extremely-rapid combustion: Pressure-tranducer information indicated extremely rapid combustion (much faster than the diesel engine which had been modified to catalytic ignition. normal diesel combustion). This was measured using an Kistler pressure transducer installed in the engine head.

2. An uncharacteristically non-sooty engine chamber interior after operation and disassembly, and

3. Quieter engine operation, with an absence of typical diesel "clatter" (confirmed by the smooth pressure trace of the combustion, which showed reduced ripples in the pressure wave).

After operation for four hours, the fasteners used to install the catalytic element burned off and the engine was shut down. The fasteners used facilitated prototype assembly and would not be part of a commercial design.

Second Prototype Engine

A second prototype was built using Inconel fasteners. These have proven durable at the engine's operating temperatures. However, fastener clearance problems in the engine used (which has a very small piston clearance at top dead center) resulted in a compression ratio of only 15/1 (compared to the engine's design compression of 19/1).

Testing of this second prototype established that

our catalytically-modified diesel can operate without loss of power output at a lower compression ratio (15:1) than the standard 19:1 ratio of the unmodified engine. The engine started up and ran smoothly. Although combustion in the catalytic engine at a nominal 15:1 compression ratio and full power output was faster than in the unmodified engine at 19:1 compression, combustion was slower than in the first prototype. It is our belief that with appropriate adjustments we can achieve extremely rapid combustion in conjunction with such lowered compression ratios. Noise levels were subjectively different, seemingly deeper in pitch. The lack of data for an unmodified engine at the same 15:1 compression ratio makes other conclusions unwarranted at this time.

PROTOTYPES TESTED UNDER THIS CONTRACT

Two prototype designs were tested under this contract for their noise characteristics and other operating parameters. The first design is designated CAT2, differing from CAT1 (used in the first two prototypes) in terms of a redesigned shape enabling a compression ratio closer to the engine's pre-catalytic design specifications. CAT2 enabled a cold cranking pressure of 33 bar, in comparison to the 35 cold cranking pressure the baseline engine could achieve (and within the 33 - 35 pressure the manufacturer specifications describe as good). As will be described further in the results section, CAT2 achieved its compression objectives durably (30 hours of operation), but at a cost of reduced catalytic ignition effectiveness compared to CAT1. (Our upcoming CAT4 design is focused upon resolving this tradeoff in favor of both catalyst activity and system durability.) CAT2 had three variants, the best of which was used in this program.

The second design tested, CAT3, eliminated the need for fasteners altogether while achieving compression (33 bar) and performing durably (12 hours of operation without apparent impairment). This design is feasible for commercial production, although catalytic ignition effectiveness was also limited in this particular variant. We expect improvements upon this design in further research to produce a fully-effective ignition system. Increasing catalytic performance is expected to be easily achievable, although it should be stressed than CAT3 in its present variant may be adequate itself to meet dynamometer objectives. Nevertheless, our CAT4 design should be superior.

The CAT3 design produced the maximum noise reduction in our tests.

EXPERIMENTAL OVERVIEW

Experimental work was directed towards evaluating two catalytic ignition designs for their ability to reduce engine noise. Sound pressure levels were measured along a 1/3 octave frequency spectrum. Two engines were used. Each engine was tested both as a conventional diesel and after modification to catalytic ignition. Changes in noise level were evaluated as a function of engine speed, load and injection timing. Differences in the overall noise level were inferred to arise from the change in the combustion process. Other operating data included in-

cylinder pressure measurements, dynamometer data (horsepower, torque and speed) and three temperature variables (inlet air, exhaust air and engine head temperature).

The Test Engine and Associated Equipment

Two 5.4 (DIN 6270B) horsepower Hatz E673 single cylinder direct-injection air-cooled Diesel engines were used the study. We originally chose this engine for our first prototype test because of its convenient availability at the time in a research configuration, and we continue to use it in this feasibility study program because a repeat of our original modification presented the least potential for unforeseen technical problems. The engine is now used in a variety of applications including small generator sets. It is our plan to expand our testing to other engines this year.

The Hatz E673 engine used in the present study has an operating speed range of 2000 to 3600RPM with performance optimized at approximately 3000RPM. The displacement is 280 ml with a bore of 73 mm and a stroke of 67mm. Compression ratio is 19:1 and actual power output is approximately 5hp at 3600 RPM The piston head is flat with a deep cylindrical air cell (approximately .5 inch diameter and 1 inches deep) into which fuel is injected. Overhead valves are operated by push rods. The engine is equipped with a centrifugal speed governor. Hatz reports the engine emits sound pressure of 85 dBA measured at 3 meters from the engine.

Two Schenck eddy-current dynamometers were used over the course of the study (with comparisons most appropriate among tests with a given dynamometer). The dynamometers each had a controller and a data acquisition console which tracked in real time horsepower, torque, RPM, and temperature.

Transient cylinder pressures were monitored using a Kistler piezoelectric pressure transducer located in the cylinder head as per Hatz recommendations. Other measuring equipment includes an AVL 361C03 shaft position encoder set to sample 600 times per revolution, an AVL Dynamic Fuel Balance, OMEGA temperature probes (for inlet air, exhaust gas (at the exit to the engine), and head surface temperature measurements), a Nicolet 4094 digital recording oscilloscope and a Bruel and Kjaer sound metering system (Model 3360). A motometer compression recording device was used to obtain cold cranking compression pressures, and a Hatz pressure gauge was used to determine injection timing.

The room had dimensions of 10 x 20 feet, with a window occupying the bulk of the outside wall and a smaller window on the inner-facing wall. The floor, roof and outside wall were concrete, and the interior walls were of a hard-faced surface. Aside from the equipment described above the space was essentially empty. The room may be characterized as a reverberating chamber. As a result, while changes in noise level in the chamber can justify relative sound pressure conclusions, the absolute levels of sound pressure are not comparable with engine results obtained in other conditions. Noise levels would be expected to be lower in an open outdoor area or an anechoic chamber.

Photographs of the experimental set-up are included as Appendix B.

Experimental Procedure

Each engine was purchased new and was broken in according to manufacturer instructions. Each engine was operated in "baseline" configuration as well as with the catalytic modification. The engine was started up using a detachable electric starter, which was removed when ignition began (in almost all cases, one to two seconds was sufficient for start-up). For the full load tests, the speed governor throttle lever was set for 3600, and the engine speed and load were controlled by the dynamometer controller. Part load operation was obtainined by adjusting the engine speed governor. Part load settings were not very reproduceable. By adjusting the governor and load control dial, the engine was brought to a given operating speed and resulting horsepower. After stabilization at the operating condition, the measuring process was begun.

Sound pressure (dB) was measured frequency by frequency with the B & K Sound Intensity System (which simultaneously displays 42 frequency bands as well as total sound pressure level). Prior to each day's set of runs, the equipment was calibrated using a B & K Pistonphone (emitting 123.9 dB). (Little calibration was required). During the runs, one individual would hold the sample probe at a height of about .6 meters above the top of the engine cylinder using a reference mark on the test stand while a second researcher would first take photographs of the CRT sound pressure level display and then manually record the same information on a record sheet. Normally, three individuals were in the chamber during sound measurements. Inasmuch as the sound pressure level did fluctuate at each frequency (more so at some frequencies than others), the individual doing the manual recording attempted to identify a median point to write down. Normally, the fluctuation was in the .2 to .3 dB range around a middle point, although it could range up to 1.5 dB at very low frequencies.

In-cylinder pressure data was monitored in real time using the Nicolet oscilloscope, with a capability to record 16K data points (approximately 13 combustion cycles) upon demand. The compression pressure data was recorded simultaneous with a printed readout record obtained from the dynamometer; immediately afterwards, the fuel flow rate was recorded manually from the AVL Dynamic Fuel Balance. Where the dynamometer was varying its indicated horsepower significantly (more than .1 HP), multiple readouts were obtained.

Noise and operating parameter measurements were taken over nine successful days of testing from January through April 1987; two with the baseline engine and seven with a catalytically-modified engine. The CAT1 design was tested prior to this contract, but its results are also included for the sake of completeness. The CAT2 design had three variants, the third and best of which was used in five of the catalytic test days. The CAT3 design was run in one variant over two days of testing. Engine 1 was used for the first four days of tests; Engine 2 was used in the last five days. Dynamometer 1 was used for the first

two days of testing until it failed; Dynamometer 2 was used for the next seven.

Summary Test Schedule

Date	Engine	Design	Variant	Dyno	Noise Runs?	Comments
1/30/87	1	CAT2	3	1	Yes	
2/2/87	1	CAT2	3	1	Yes	Best SFC
2/20/87	1	Baseline		2	Yes	
2/27/87	1	CAT2	3	2	Yes	
3/5/87	2	Baseline		2	Yes	
3/10/87	2	CAT2	3	2	Yes	
3/11/87	2	CAT2	3	2	No	Repeat of 3/10
4/6/87	2	CAT3		2	Yes	Lowest noise
4/7/87	2	CAT3		2	Yes	Lowest noise

DISCUSSION OF EXPERIMENTS

CAT2 and CAT3 designs were tested to determine the effect of an in-cylinder catalyst on combustion noise. As the chart below indicates, while both designs reduced noise, CAT3 was the more effective design, producing as much as a 5 dB improvement in total sound pressure level. Because this design was generally superior to CAT2, we focus more strongly in this discussion upon its results.

Relative Total Sound Pressure Levels (db)
CAT2 and CAT3 minus Baseline
(Injection Timing Optimized)

Change in Total Sound Pressure Level

Engine Speed	Load	CAT2	CAT3
3600	Full	-1.1	-3.8
3000	Full	n.s.	-4.9
2500	Full	- .9	-4.9
3000	Part	- .7	-4.4

n.s.: Not significantly different

To the ear, the catalytic engine operated at a lower pitch with less apparent higher frequencies.

Detailed sound pressure levels by frequency are discussed below after other issues are dealt with.

Injection Timing Variations

Both catalytic designs were found to change ignition delay,

and it was found that advancing the injection timing would improve catalytic performance (as indicated by combustion pressure wave performance). When baseline timing was also advanced (from the factory settings), performance was impaired and engine roughness increased.

2500 RPM

The optimum catalytic injection timing varied with engine speed, earlier injection being required at higher engine speeds for maximum power and fuel economy. At 2500 RPM, improved performance was obtained at the standard injection timing. However, at higher speeds advanced timing was required. As noted in the theoretical discussion of catalyst performance, the optimum injection timing is expected to be a function of catalyst configuration inasmuch as catalyst temperature and geometry determine ignition delay in a catalytic engine.

As noted above, it was found that rated power with a lower measured total sound pressure level could be obtained with the catalytic engine at 2500 RPM without advancing the injection timing. This is shown by the comparison below (standard injection timing).

	Baseline	CAT3
	db (hp)	db (hp)
2500 RPM	113.9 (3.2)	109.0 (3.3)

Note that a 4.9db improvement was obtained at 2500 and full power. Maximum power was about the same in both tests. Advancing the injection time three degrees with the CAT3 piston increased noise level at this speed slightly and decreased power slightly (110.7db at 3.2hp), as a result of too early combustion. Sound pressure level was still 3.2db below the baseline run even though the peak combustion pressure was higher, as shown by a comparison of figures 1 (baseline piston) and 2 (catalytic piston). Note that with the catalytic piston the cycle to cycle variations are somewhat reduced and the curves appear to be somewhat smoother. Careful examination of figure 2 shows that combustion started before top dead center. Inasmuch as advancing the injection timing increased the peak combustion pressure as compared to the CAT3 run with standard injection timing, it is believed that the power level was decreased by early combustion during the compression stroke. The optimum timing may lie between the two values tested.

3600 RPM

In contrast to the results at 2500 RPM, with the standard injection timing the full load power at 3600 RPM was decreased by use of a catalytic piston. However, with optimization of injection timing it was possible to not only reach but to exceed baseline engine power levels. Moreover, this result was achieved at a total sound pressure level significantly below that of the baseline engine. This is shown in the following tabulation.

Injection	Baseline db	(hp)	CAT3 db	(hp)
Standard	116.1	(5.1)	113.8	(4.6)
-1 degree	117.7	(4.9)	-	-
-3 degrees			112.3	(5.4)
-4 degrees			113.1	(5.5)
-5 degrees			113.1	(4.9)

In the catalytic piston tests, it should be noted that the engine power first increased and then decreased as injection timing was advanced. Unlike the base case engine however, engine noise did not increase with advanced timing. Examination of the cylinder pressure traces in Figures 3 and 4 indicates that with the standard injection timing combustion was slightly delayed and cycle to cycle combustion variations were increased for the catalytic run as compared to the baseline run. However, the combustion pressure wave exhibited fewer ripples than the baseline run resulting in less high frequency noise. In the three catalytic runs with advanced injection timing, not only were the pressure curves smoother but combustion occurred closer to top dead center (earlier), cycle to cycle variations were reduced, and peak pressure was increased. This is shown in figures 5 (approximately -3 degrees crank angle vs standard) and 6 (-4 degree crank angle). In all three catalytic runs with advanced injection timing the total sound pressure level was lower than in the run with standard injection timing in spite of the significantly higher peak pressures, a result believed to be primarily a consequence of fewer high frequency oscillations. In line with the higher peak pressures, at 3600 RPM the primary thirty cycle combustion pulse frequency sound pressure increased monotonically with increase in peak pressure as indicated below.

	db (31.5 Hz band)	% Peak Pressure Incr.
Std	81.4	-
-3 degrees	83.7	5
-4 degrees	87.2	10
-5 degrees	89.2	28

Note that in the standard injection run there was no visible combustion pressure wave at TDC (Figure 4) and the peak pressure appears to be little different than the baseline compression pressure (Figure 3). Yet at injection -3 degree crank angle the pressure wave is clearly moving notably higher than in the baseline case (compare figures 5 and 3).

<u>Catalytic Noise Sensitivity to Injection Timing Advance</u>

An important finding of the present study is that the noise level of a catalytic engine appears to be relatively insensitive to fuel injection timing within the range tested. This can be seen by examination of the sound spectra data as shown in figures 7-9 (CAT3 design) and figures 10 and 11 (CAT2 design). All figures show a remarkable consistancy for a given speed. This has important consequences for engine efficiency as will be

discussed below. Note that although the sound spectrum at a given speed changes very little with changes in injection timing, there are changes with engine speed and with design of the catalytic piston.

As noted above, the noise level of a catalytic engine is relatively insensitive to fuel injection timing. Thus, injection of the fuel can be timed to optimize power level and fuel economy without a significant noise penalty. Actually, from the limited data available it appears that the fuel injection timing for for minimum noise may correspond fairly closely to the injection timing required for maximum power, as appears to be the case for the 3600RPM full load data cited herein. The reason for this seems to be that as injection timing is advanced in a catalytic engine, cycle to cycle variations are reduced offsetting the effect of the higher peak pressure. Increased noise can be expected if timing is advanced to the point where significant combustion occurs during the compression stroke decreasing power and greatly increasing peak pressure.

Based on the data discussed above, it appears that with the CAT3 piston design the injection timing for optimum performance is a strong function of engine speed unlike the original prototype design. Nevertheless the CAT3 design is important since it represents a variation readily amenable to commercial production. Although the part load data is too limited to draw firm conclusions, it is believed likely that the optimum injection timing for best performance at a given speed will also be a function of engine load and inlet air temperature with the CAT3 piston. Use of a suitable electronic fuel injection system would appear to offer the possibility of achieving optimum injection timing over a broad range of operating conditions. From discussions with several researchers at the 1987 S.A.E. meeting in Detroit, it is evident that this is a significant advantage of such systems with conventional diesel engines.

Effect of Changes in Speed

As the chart below indicates, total sound pressure level did increase with speed for both the catalytic and baseline engines. Because the 2500 RPM speed was quieter at standard injection and because the catalyst in these tests remains less active than it may become, we feel it is too early for any comparative conclusion on this topic.

	Baseline		CAT3	
	dB	H.P.	dB	H.P.
3600	116.1	5.1	112.3	5.4
3000	115.5	4.6	110.6	4.4
2500	113.9	3.2	110.7	3.2

Note: CAT3 engine with injection at - 3 degree crank angle vs standard.

Pressure Wave Analyses

An analysis of the combustion pressure waves collected and stored by the digital recording oscilloscope allows the following observations:

1. Peak pressures in the injection-optimized catalytic runs were higher than in the baseline.

2. While the rate of pressure rise in the combustion chamber was generally steeper than the baseline, the change in the rate of pressure rise (the second derivative of pressure) was smoother, especially near the top of the curve.

3. Catalytic combustion periods appeared shorter (more rapid combustion) than baseline combustion.

4. Cycle to cycle variations both in peak pressure and in general combustion wave shape were reduced in the catalytic runs.

5. Local variations in the pressure wave (ripples) were reduced in the catalytic runs.

Fuel Economy

Fuel economy measurements showed CAT3 enjoyed approximately the same fuel economy as the baseline engine. Variations are well within the experimental error.

Full Load RPM	Baseline H.P.	Baseline Specific Fuel Cons. (kg/hp-hr)	Catalytic (CAT3) H.P.	Catalytic (CAT3) Specific Fuel Cons. (kg/hp-hr)
3600	5.1	.64	5.5	.64
3000	4.6	.53	4.4	.54
2500	3.2	.60	3.3	.57

Note: CAT3 engine with injection at - 3 degree crank angle vs standard.

We do not expect catalytic engine fuel economy to be optimized until the catalyst itself is made more active.

Exhaust Temperature

Exhaust temperatures varied significantly with injection timing and with catalytic design. The catalytic runs with the best fuel economy had the lowest exhaust temperatures, and the lowest exhaust temperatures at a given speed and load were with catalytic runs. On the other hand, the highest exhaust temperatures obtained were also catalytic. We believe further studies are needed to evaluate temperature effects.

Sound Pressure by Frequency Analysis

Figures 12 through 15 show comparative sound pressure levels

by 1/3 octave frequency from 20 Hz to 10,000 Hz, together with total sound pressure level. The figures compare baseline vs catalytic noise levels for each of four operating conditions: 3600 RPM, full load; 3000 RPM, full load; 2500 RPM, full load; and 3000 RPM, part load, respectively. Each figure consists of three bar charts: the first chart indicates noise by frequency first for the baseline case, the second chart shows noise for the catalytic case (CAT3 with injection at -3 degrees crank angle), and finally the difference is charted with negative bars indicating catalytic noise reductions.

In reviewing these results, two items should be kept in mind: first, these noise levels are after the results of engine structural attenuation, and second, the most important frequencies from a human detection point of view are in the 500 Hz to 5000 Hz range. The fact that the engine test cell was a reverberating chamber also makes analyses most significant when they are comparing catalytic with baseline within a frequency, with comparisons between frequencies more subject to error.

Of special importance to this study, not only are the total sound pressure levels lower for the catalytic case, but the reductions in SPL in the highest human detection range are greater than the overall sound pressure reduction. This is true in each condition tested.

There are specific variations which may be of interested. First, the frequency corresponding to the repetition rate of combustion (31.5 Hz for 3600 RPM, 25 for 3000 RPM and 20 for 2000 RPM) are actually reduced across the board for the catalytic runs. Higher peak pressure results for the catalytic engines work against this result, but possibly the smoother peak curvatures in the catalytic runs more than offsets the effects of higher peak pressure at the repetition rate of combustion.

Second, as expected, the combustion pressure pulse rate frequency shifts with engine speed having a nominal value of 30Hz at 3600 RPM, 25Hz at 3000 RPM, and 21Hz at 2500 RPM. The changes in sound spectra with speed are shown in Figures 16 and 17. It should be noted that there is also noise excitation at double these frequencies possibly a result of piston slap during the exhaust and inlet strokes in addition to any harmonics generated by the combustion pressure wave.

Third, there are some frequencies which are higher for the catalytic runs. These vary by speed and load, and are most counter to the overall trend in the 3600 RPM/full load case (50 - 63 Hz) and the 2500 RPM/full load case (250 Hz, with a lesser version in the 3000 RPM/full load case). We have no particular explanations for these anomalies, except to note that they are occurring at frequencies which are outside the central human hearing range. One possibility is that the dynamometer load cell is involved. Further study will involve FFT analysis of the in-cylinder pressure data to learn if these local relative peaks originate in the cylinder or outside.

Catalytic Ignition System Durability

Although the present program did not allow for life testing

of catalytic pistons, no physical deterioration was noticed in the pistons used in the present study (30 hours approximate running time on CAT2; 15 hours on CAT3). Although this result is indicative of the likelihood of a reasonable catalyst life based on experience with gas turbine combustor catalysts, long term life studies must be carried out.

Increased Structural Strain

Another question which must be addressed is the increased structural and bearing loadings which accompany increases in power output. In fact in the present test there was some evidence of increased bearing wear in tests with the CAT2 piston, although this may be due in part to the extensive fuel injection timing changes attempted with this engine (it responded less smoothly to these changes than did CAT3). Nevertheless, peak pressure increases have the potential to present a problem.

One solution to the increase in peak pressure may actually improve engine efficiency and possibly also further reduce noise. In our discussions with engine researchers at the recent S.A.E. meeting, there was general agreement that the optimum compression ratio for maximum efficiency is a trade-off between thermodynamic efficiency and mechanical losses. With present mechanical designs it was felt that this optimum compression ratio is in the range of 12 to 14/1. In principal, a catalytic ignition engine can be designed to operate at a very wide range of compression ratios. Thus, one way of lowering mechanical stresses and also improving efficiency may be to operate a catalytic engine at a lower compression ratio. Relevant to this possibility is the second prototype test of the CAT1 design, which occurred at a nominal 15/1 compression ratio (vs a baseline design compression ratio 19/1). This engine started and operated normally.

SUMMARY OF EXPERIMENTAL RESULTS

While relative improvements varied depending upon factors such as load, speed, and injection timing in the present tests, the benefits of catalytic control of ignition with respect to noise has been demonstrated.

1. The catalytic designs were demonstrated to be capable of reducing noise and increasing combustion speed. With proper injection timing, much higher peak pressure levels could be achieved with combustion better positioned with respect to top dead center. Noise was significantly reduced, not only totally but also concentrated within the audible range.

2. Injection timing advances improved the combustion in the catalytic engine, raising peak horsepower levels and improving fuel economy. In contrast, advances in the baseline engine impaired performance. This is not unexpected in light of the fact that the engines as received were optimized for conventional operation. In contrast to the baseline engine, the catalytic engine demonstrated that combustion could be timed at top dead center even at the top engine operation speed. With the particular catalytic design and engine used, advancing the start of injection improved performance, although in other engines

positive results may arise from moving the injection closer to TDC (ie. retarding injection timing). Although further analysis was made of the effects on performance and noise on the changes in injection timing, the conclusions below generally deal with catalytic runs with adjusted injection timing. The data indicates a 3 degree advancement in timing produced the best results at the top rated speed, although the curve of performance beyond this advance is relatively flat.

3. The catalytic engines in these tests did not reduce ignition delay and combustion time as well as our original prototype. The likely cause is reduced catalyst activity arising from our more durable CAT2 and CAT3 designs. We believe the solution involves relatively straightforward engineering which we are incorporating into our CAT4 prototype design.

4. Every injection-optimized catalytic run had lowered total sound pressure vs its comparable baseline run. Noise reductions for the CAT3 design ranged from a low of 3.8 db at 3600 RPM to a high of 4.9 db at 2500 RPM and 3000 RPM.

5. Noise reductions have been concentrated in the speech frequency and high human sensitivity ranges. Thus perceived noise in the prototypes has been reduced even more than the total sound pressure level improvement would indicate. This can be more clearly seen in the frequency analyses of Figures 12 through 15.

6. In comparison to the baseline engine, a higher peak internal combustion pressure at TDC in the catalytic engine did not lead to a higher exterior noise level.

7. The rate of change in the combustion pressure wave appeared less for the catalytic runs than the baseline runs. This was most pronounced in a smoother peak to the pressure curve.

8. Cycle to cycle variations in combustion pressure waves have been reduced.

9. The catalytic engine has had smoother combustion pressure waves (reduced ripples). As with cycle to cycle consistency, we believe that improving the catalyst's effectiveness will further reduce these local oscillations.

10. The catalytic engine appeared relatively insensitive with respect to noise level to variations in injection timing. Since injection timing adjustments were helpful in improving other performance parameters, this may indicate that catalytic engine timing can be optimized without noise considerations. Advancing timing in the baseline engines increased noise level.

11. The catalytic engine can run well at least as low as 15/1 compression compared to a 19/1 design for the baseline engine.

12. The catalyst proved durable during tests (max 30 hours for one piston; 15 hours for CAT3).

13. The piston-connecting rod bearings in the CAT2 tests showed some evidence of increased wear. This needs to be studied

further.

14. Engine head temperature and exhaust temperature effects need more study. In some cases exhaust temperature was increased; in others it was reduced compared to baseline.

15. Significant further improvements appear feasible.

CONCLUSIONS

The catalytic ignition engine shows significant potential in reducing noise levels of diesel fuel engines. Early prototype tests have demonstrated 4 to 5 dB of noise improvedment in steady state conditions with no loss of fuel economy and with an increase in power. Furthermore, the noise reduction appears concentrated in the audible range (producing an even greater dB improvement to the ear). In addition, the noise improvements produced by this technology involve combustion noise reductions which are likely to be additive to other engine noise reduction technologies. Finally, it is believed that catalytic ignition design improvements would lead to an even greater reduction in noise.

The catalytic ignition engine also shows the potential for a wide range of operating improvements compared to a diesel engine. These potential improvements include fuel economy, power, emissions, cold-starting, fuel quality insensitivity and true multifuel capability. With prototypes created from existing diesel engines at an estimated high volume manufacturing cost of approximately $10 per cylinder (above the cost of the engine itself), the catalytic ignition engine appears to entail relatively low added purchase cost. A retrofit capability also exists, with similar low costs above the expense of a normal engine overhaul.

As a consequence of its many promising advantages, the catalytic ignition engine represents an important technology with the potential for wide benefit throughout the U.S. economy. Early discussions with selected engine manufacturers has proven the existence of significant manufacturer interest in this technology.

Catalytic ignition technology is compatible and synergistic with advanced diesel engine technologies now being supported by the Army.

NEXT STEPS AND RECOMMENDATIONS FOR FURTHER STUDIES

Combustion studies are now continuing with our next catalytic design (CAT4), with testing expected in the summer of 1987. This design is directed towards combining the durability of the CAT3 design with the high catalytic activity of the CAT1 design. In addition, we intend to attempt an FFT analysis of the in-cylinder pressure data recorded by the digital oscilloscope

used in this study: such an analysis would produce in-cylinder frequency data which could be used to further verify frequency shift conclusions.

Private capital has been raised to establish an independent testing facility with limited equipment for further engine tests (testing to date has been in subcontracted facilities).

A number of study areas are feasible at this stage to continue to develop this technology. We suggest the following course of development.

1. Optimization of an active, durable catalytic design: As noted above, CAT4 may be this design as it relates to the combustion chamber, but it is likely that additional optimization work will be valuable. This would include a study of the effect of catalyst configuration and placement on noise and performance. Combustion chamber design also needs to be evaluated and optimized for catalytic operation. Durability studies are needed to discover if other engine components need adjustment.

These prototype tests have indicated catalytic ignition engine fuel economy to be similar to the baseline, with power slightly higher than baseline. Because it was not the focus of this work, we have only lightly touched upon the potential efficiency and power advantages of the catalytic ignition engine, but with increased catalyst activity there is a good likelihood that this technology will produce superior performance in these areas.

2. Extension of the technology to other diesel engines of interest: While tailoring of the technology to specific engines is likely to be a cáse by case undertaking, we intend at an early stage to work to tailor the technology to major types of diesel engines. An important component of this project will be the development of a model which can be used to simulate the technology's application and impact upon existing diesel designs. Laboratory work would help calibrate this model. In addition, the move to multicylinder engines is included in this project area, but this will occur only after we optimize in a single cylinder engine.

3. Compression ratio studies: These would explore reductions in catalytic engine compression ratio as they impact on operating parameters including noise.

4. Injection optimization work: Injection timing, duration and fuel atomization are all important variables which could help the catalytic ignition engine achieve its potential.

5. Multifuel and fuel quality insensitivity studies.

6. Cold-start studies: Obviously related to 5 above, this would focus upon methods of improving cold start beyond current capabilities and in the process would help define the parameters important in the operation of a catalytic engine.

These studies enable us to make a prototype which could have

improved fuel economy, power, fuel and noise characteristics, resulting in major U.S. engine manufacturer interest in this engine. Preliminary manufacturer interest has already been developed. This work could also produce a viable retrofit kit technology for converting existing engines in the field to catalytic ignition.

Catalytic ignition technology is quite young. It is too early to know all the areas in which it could have a beneficial impact. However, these tests have proven a noise advantage, and we believe the fuel economy and power advantages will follow from improved designs. The multifuel advantage is likely already present, if untested. There is thus the strong potential for a myriad of specific benefits which catalytic ignition can convey upon the Army's use of generator sets, upon Army engine use and upon U.S. internal combustion technology in general. Continued Belvoir support of this technology's development will be invaluable in helping the catalytic ignition engine achieve its potential.

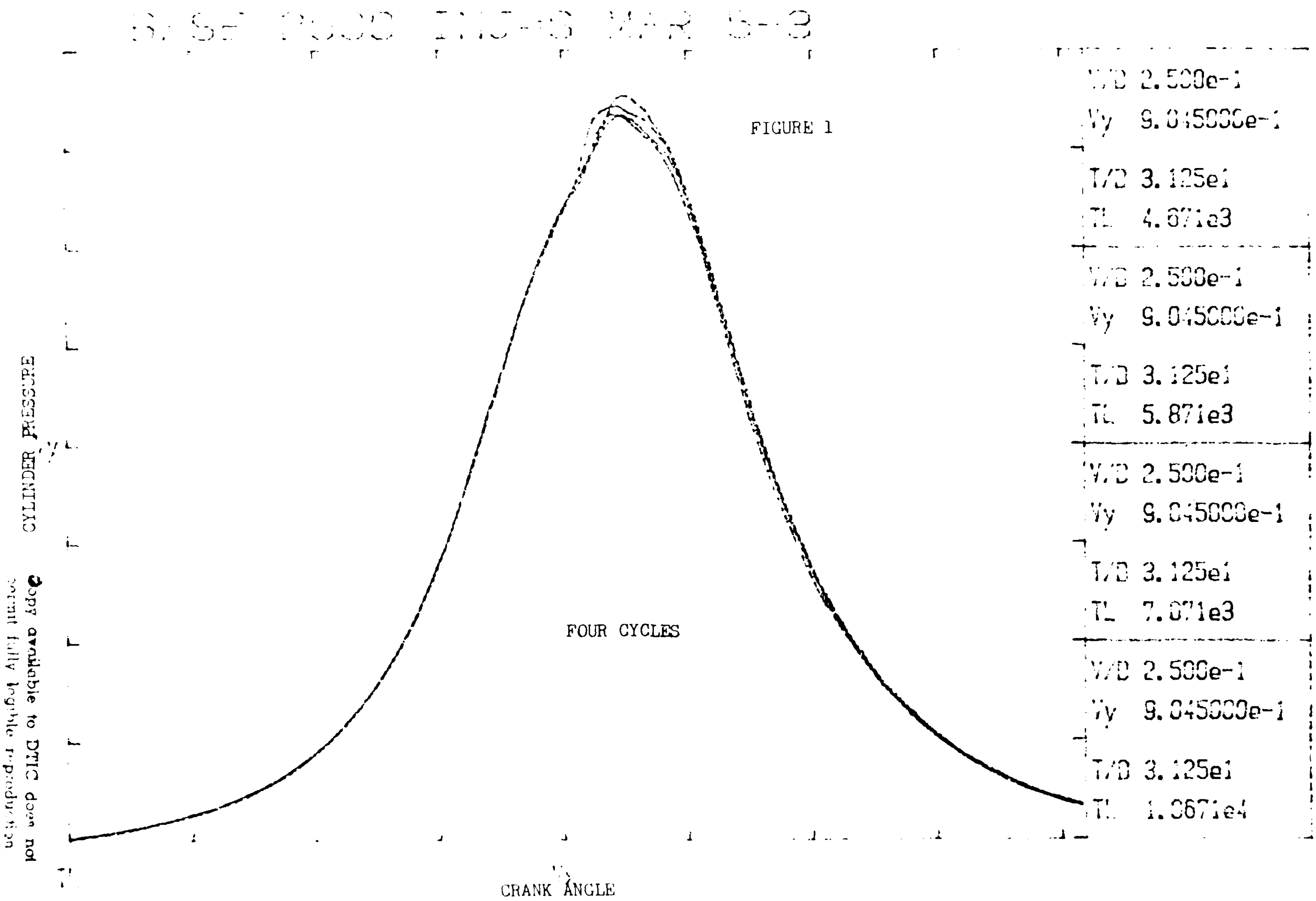

FOUR CYCLES
CYLINDER PRESSURE
CRANK ANGLE
V/D 2.500e-1
Vy 9.045000e-1
T/D 3.125e1
TL 4.871e3
V/D 2.500e-1
Vy 9.045000e-1
T/D 3.125e1
TL 5.871e3
V/D 2.500e-1
Vy 9.045000e-1
T/D 3.125e1
TL 7.871e3
V/D 2.500e-1
Vy 9.045000e-1
T/D 3.125e1
TL 1.0871e4

FIGURE 1

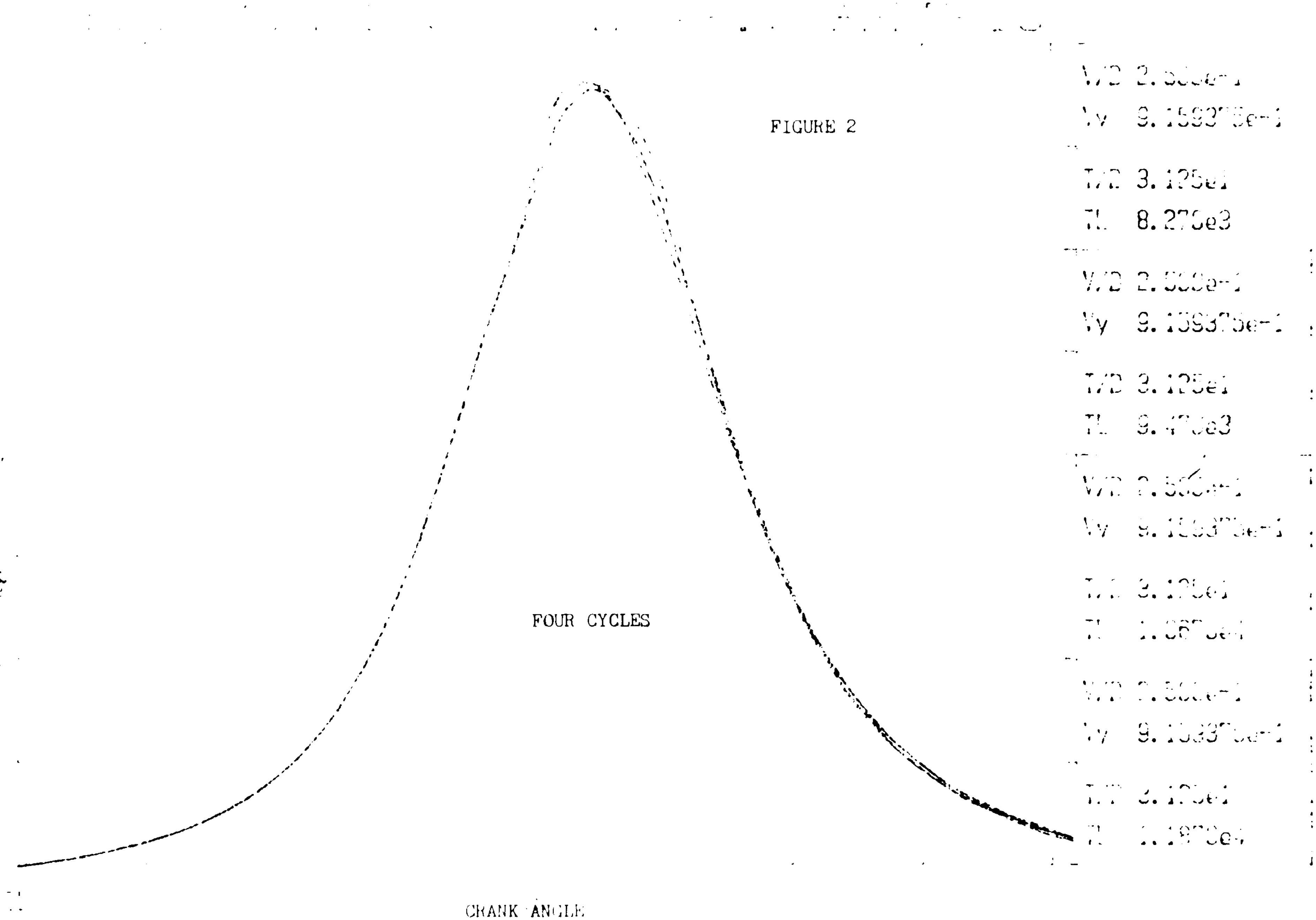
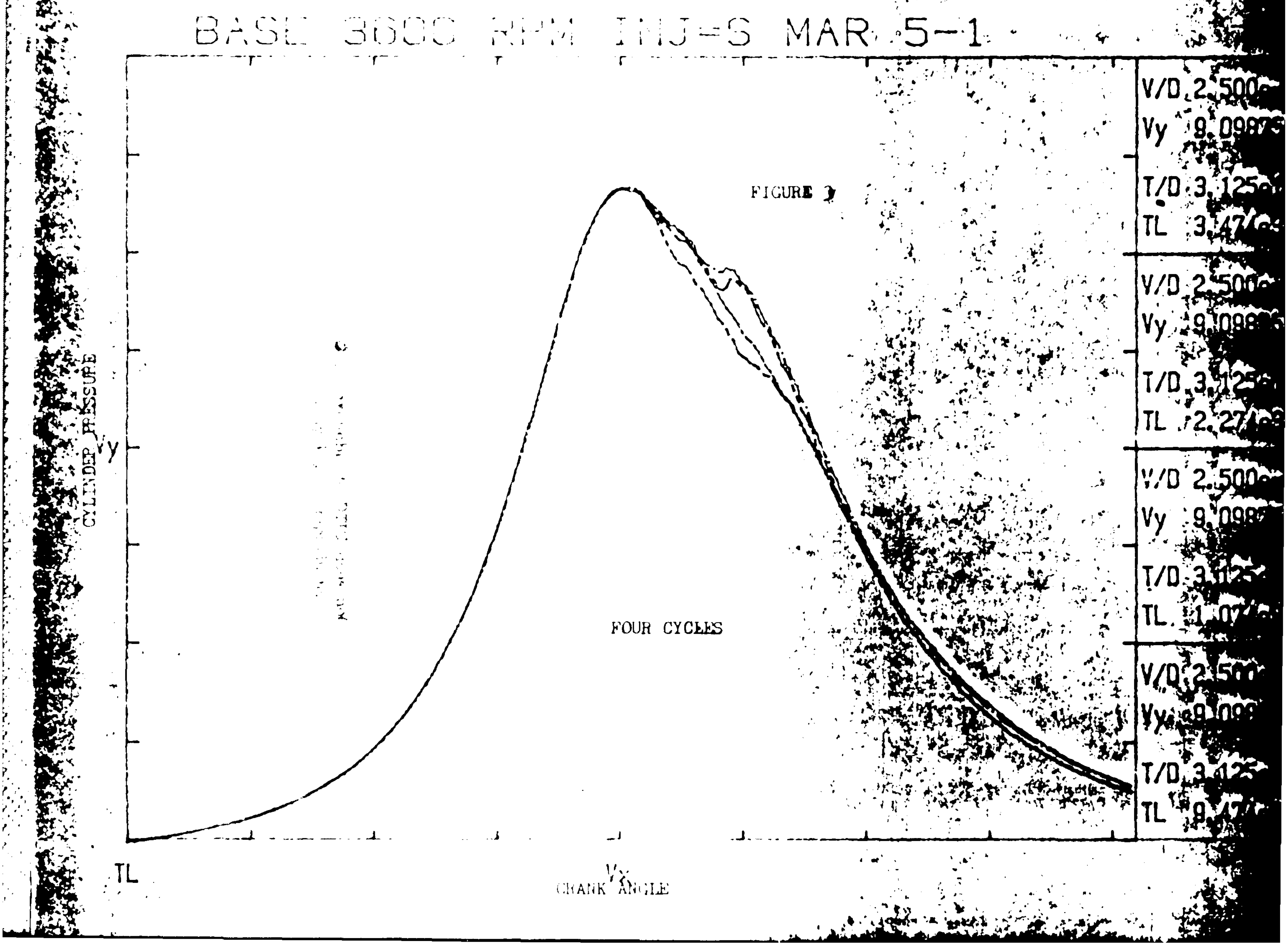

FOUR CYCLES
CYLINDER PRESSURE
CRANK ANGLE
T/D 3.125e1
TL 8.270e3

FIGURE 2


BASE 3600 RPM INJ=S MAR 5-1
FIGURE 3
FOUR CYCLES
CYLINDER PRESSURE
Vy
TL
Vx
CRANK ANGLE
V/D 2.500
Vy 9.0987
T/D 3.125
TL 3.47
V/D 2.500
Vy 9.0988
T/D 3.125
TL 2.27
V/D 2.500
Vy 9.098
T/D 3.125
TL 1.07
V/D 2.500
Vy 9.09
T/D 3.125
TL 9.47

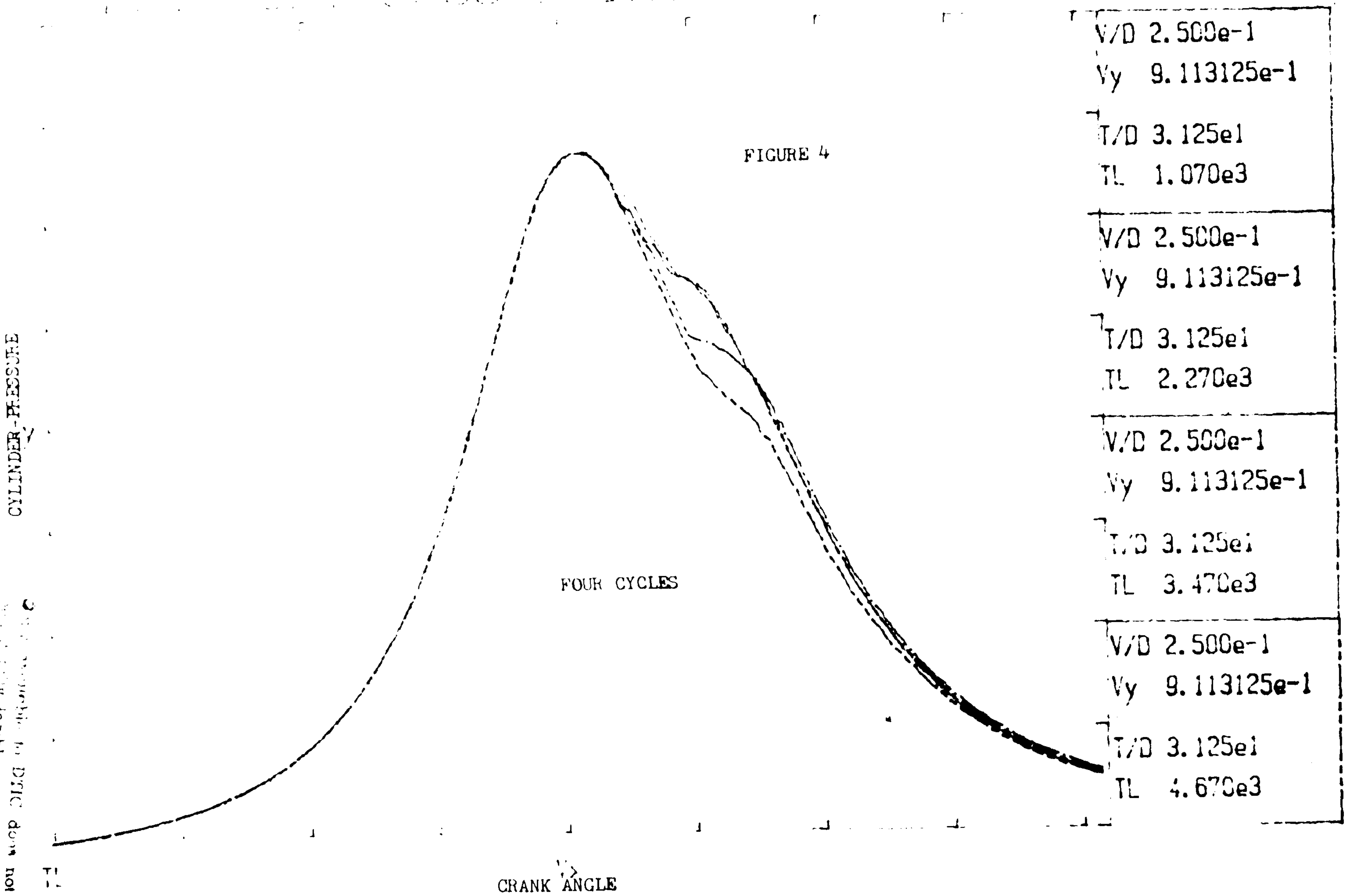


FIGURE 4
FOUR CYCLES
CYLINDER-PRESSURE
CRANK ANGLE
V/D 2.500e-1
Vy 9.113125e-1
T/D 3.125e1
TL 1.070e3
V/D 2.500e-1
Vy 9.113125e-1
T/D 3.125e1
TL 2.270e3
V/D 2.500e-1
Vy 9.113125e-1
T/D 3.125e1
TL 3.470e3
V/D 2.500e-1
Vy 9.113125e-1
T/D 3.125e1
TL 4.670e3

FIGURE 5

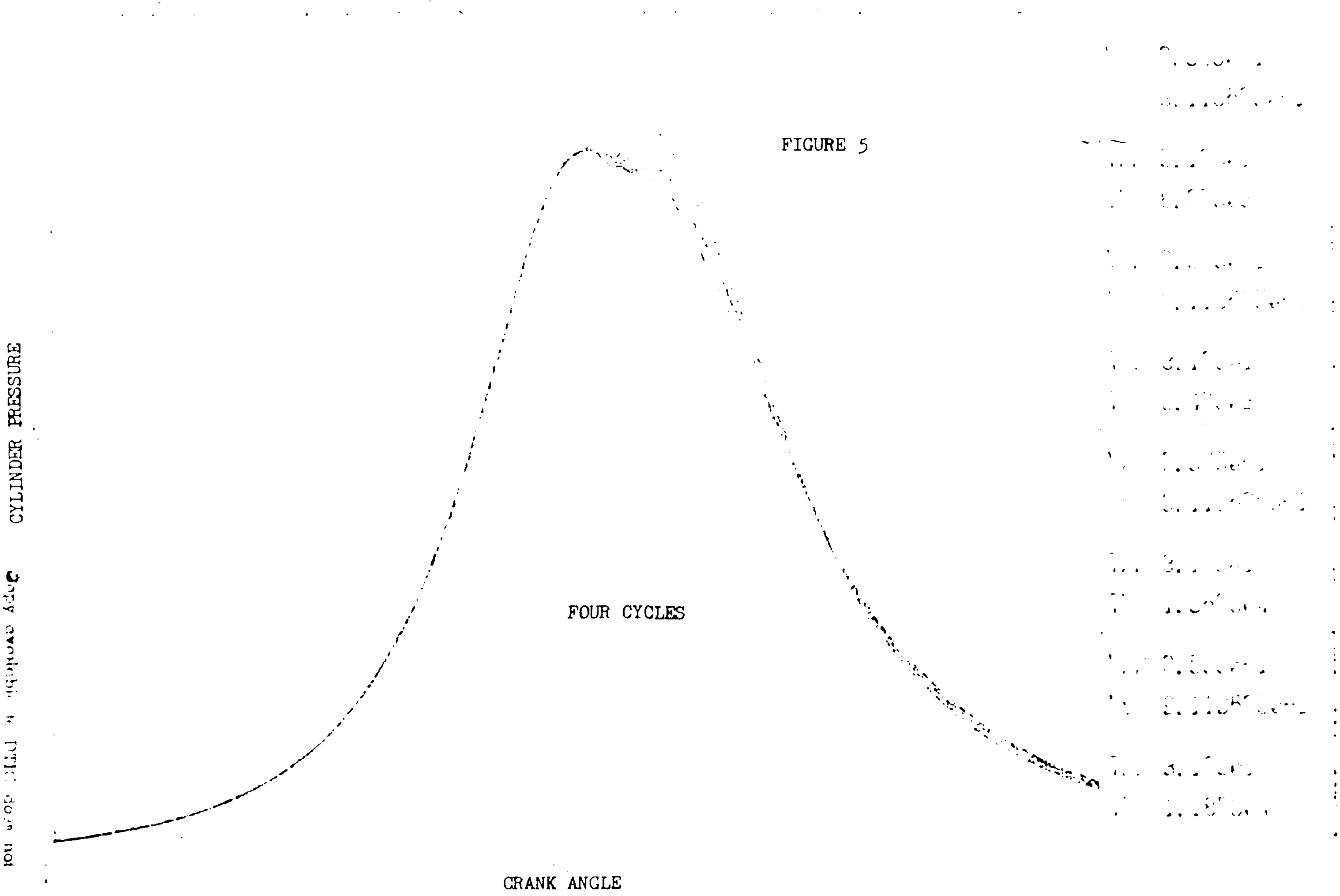
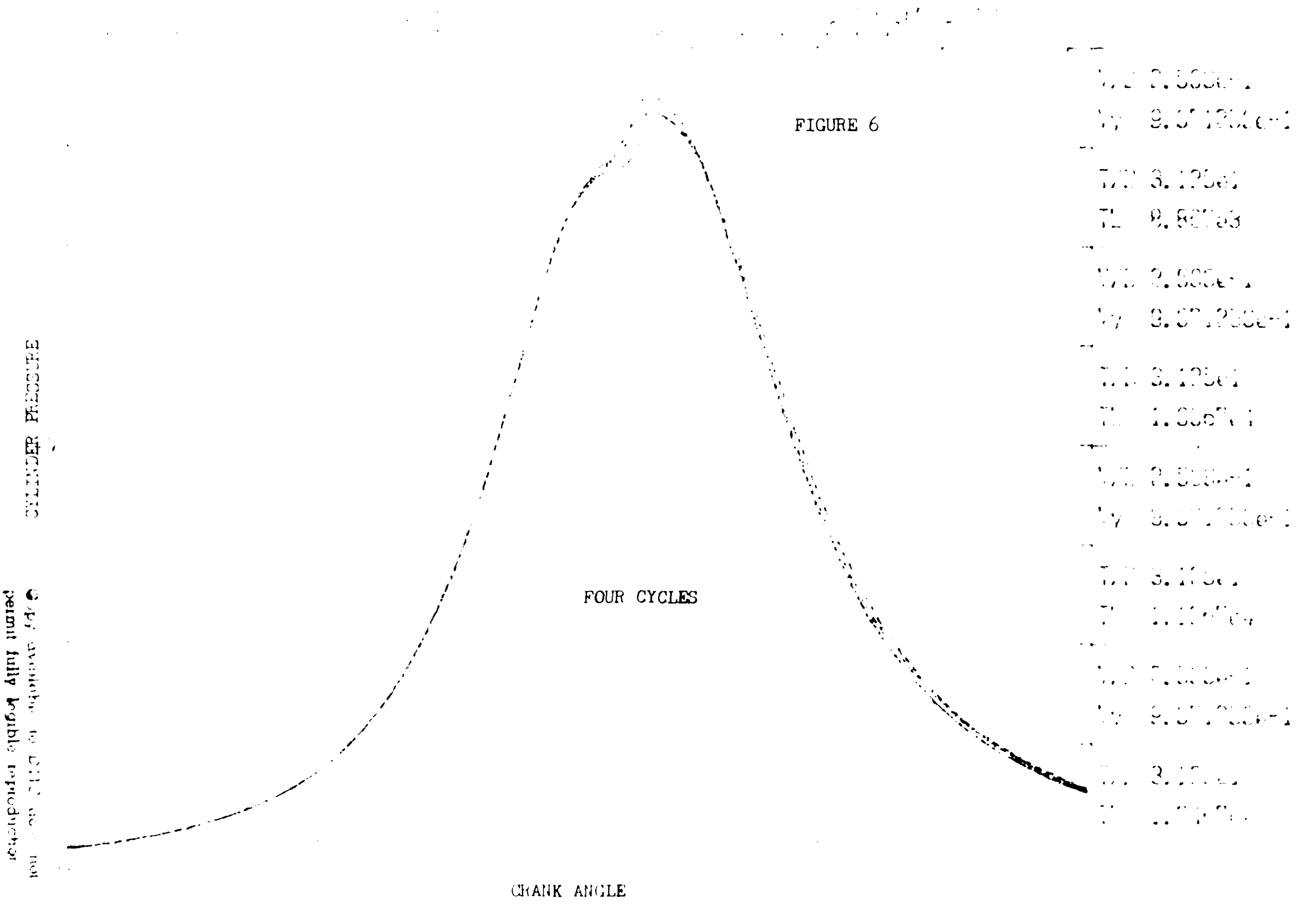


FIGURE 6



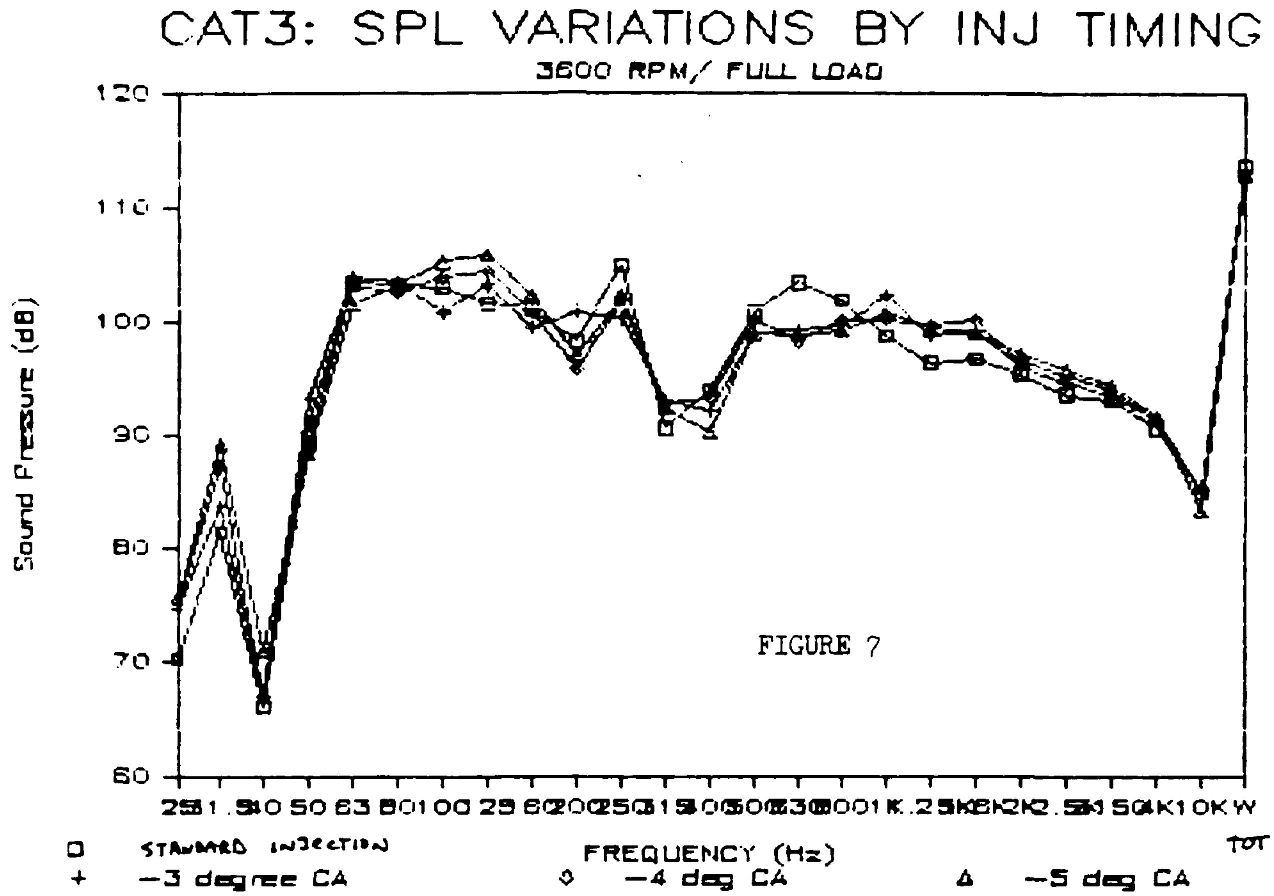


FIGURE 7

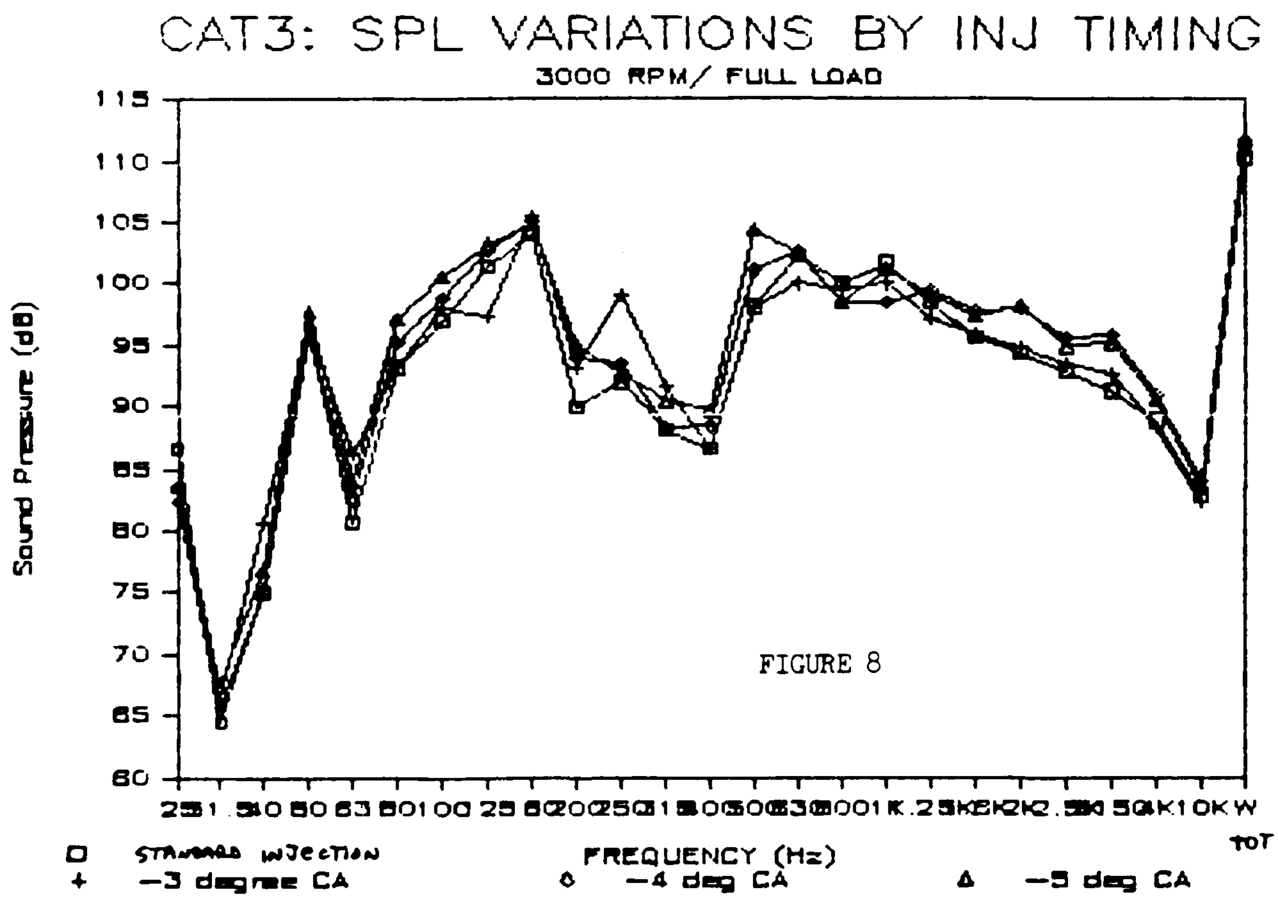


FIGURE 8

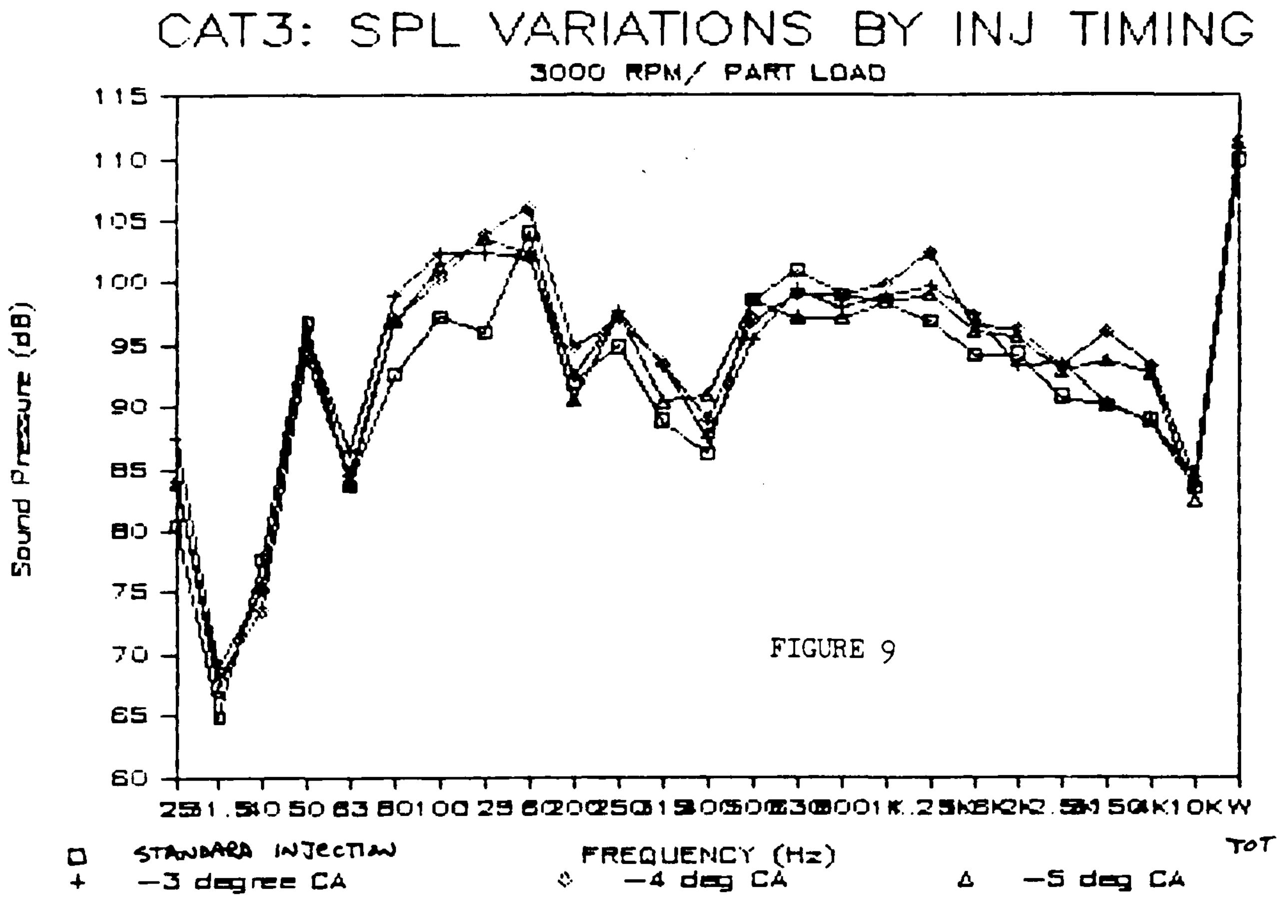

CAT3: SPL VARIATIONS BY INJ TIMING
3000 RPM/ PART LOAD
Sound Pressure (dB)
115
110
105
100
95
90
85
80
75
70
65
60
FREQUENCY (Hz)
TOT
STANDARD INJECTION
−3 degree CA
−4 deg CA
−5 deg CA

FIGURE 9

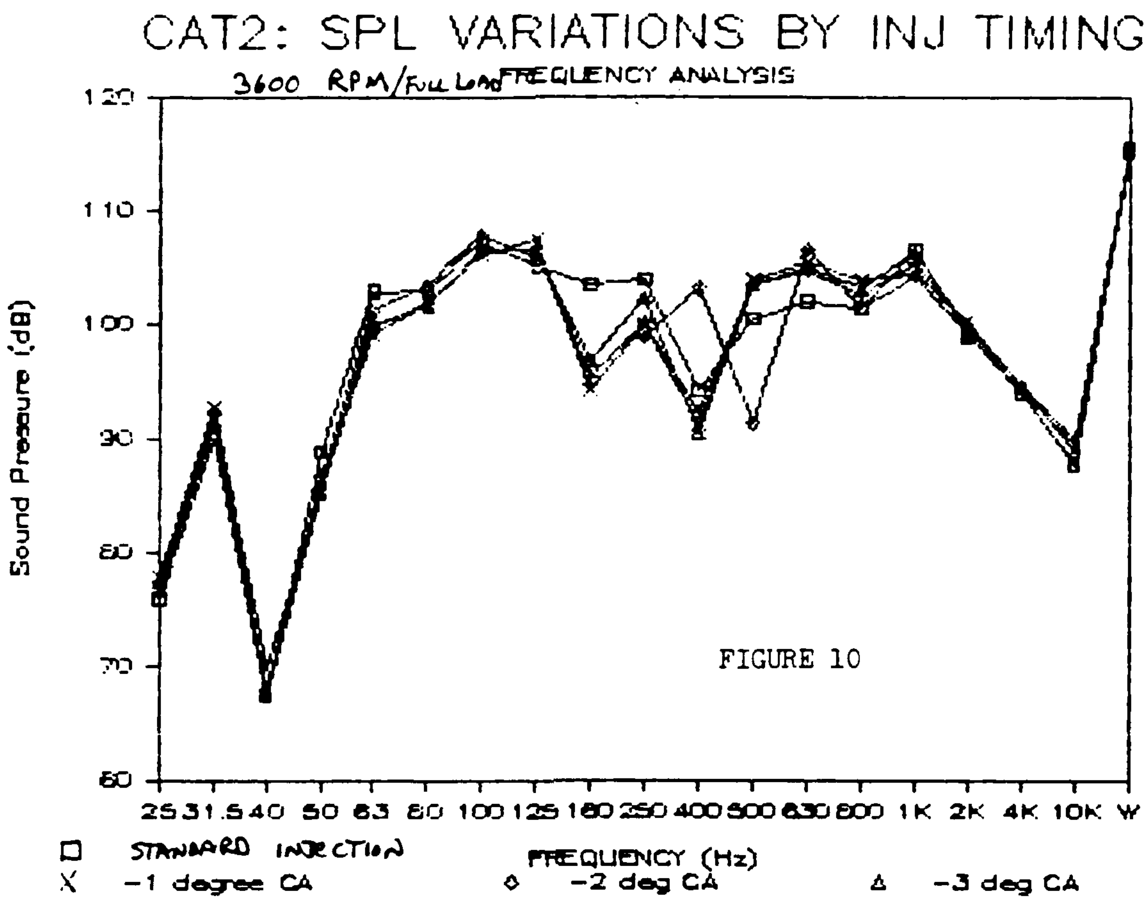


FIGURE 10

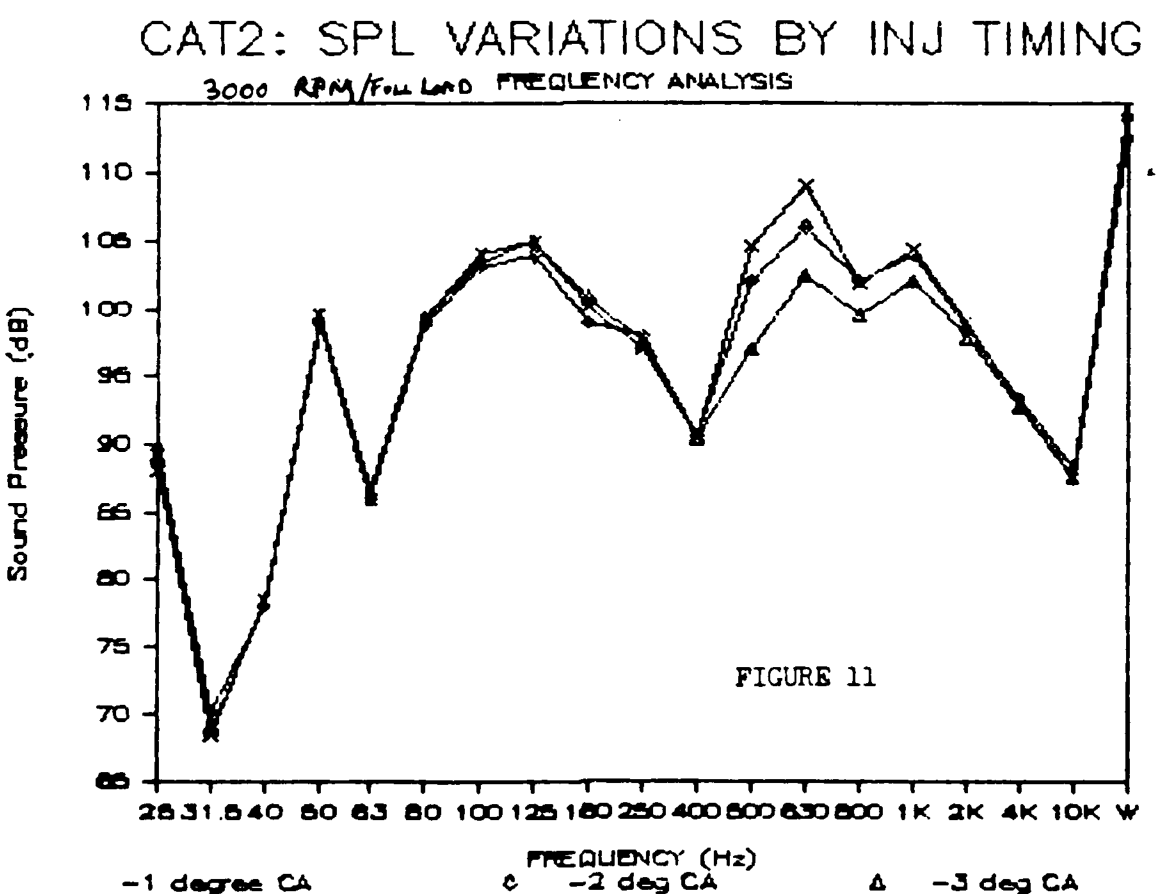


FIGURE 11

FIGURE 12

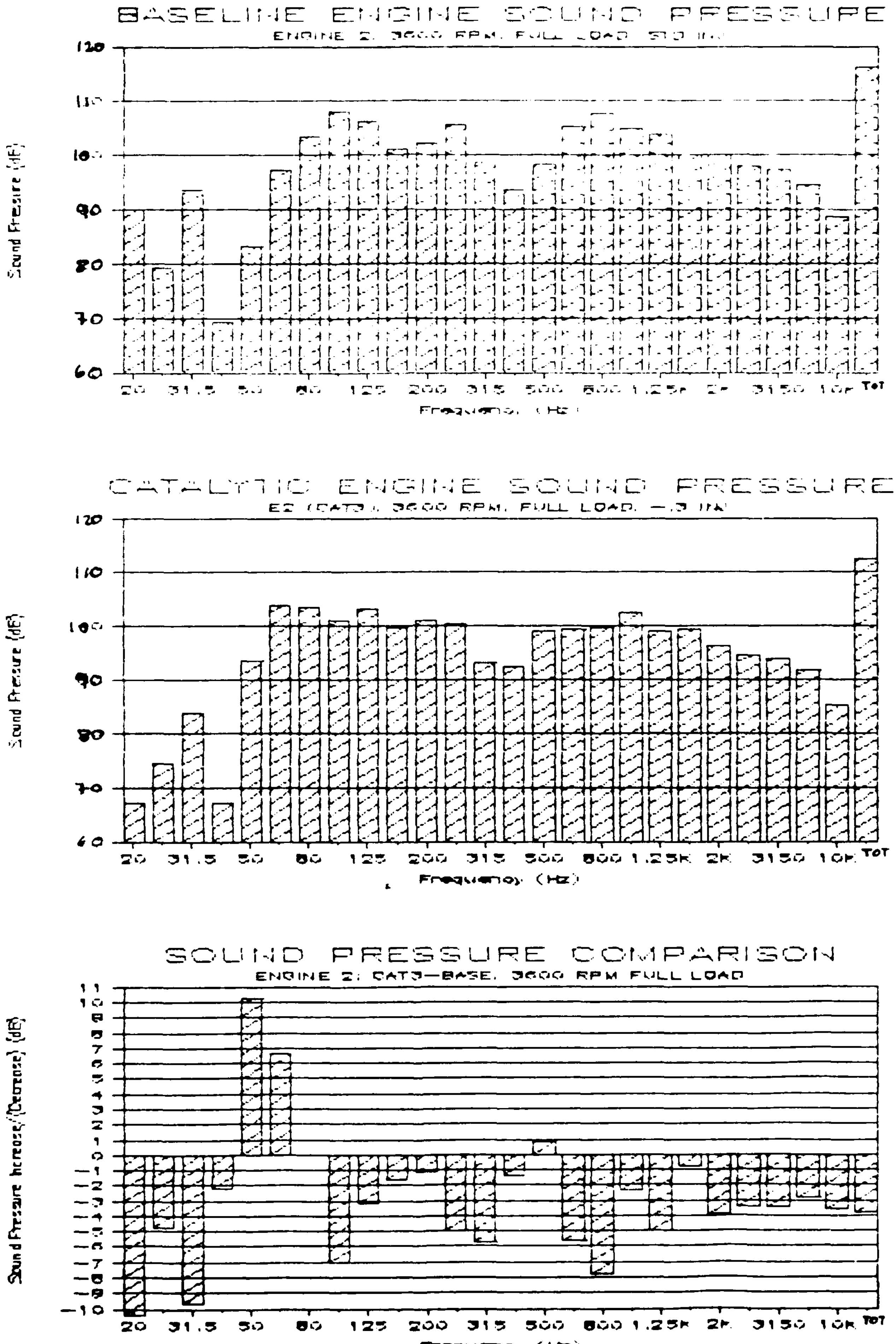
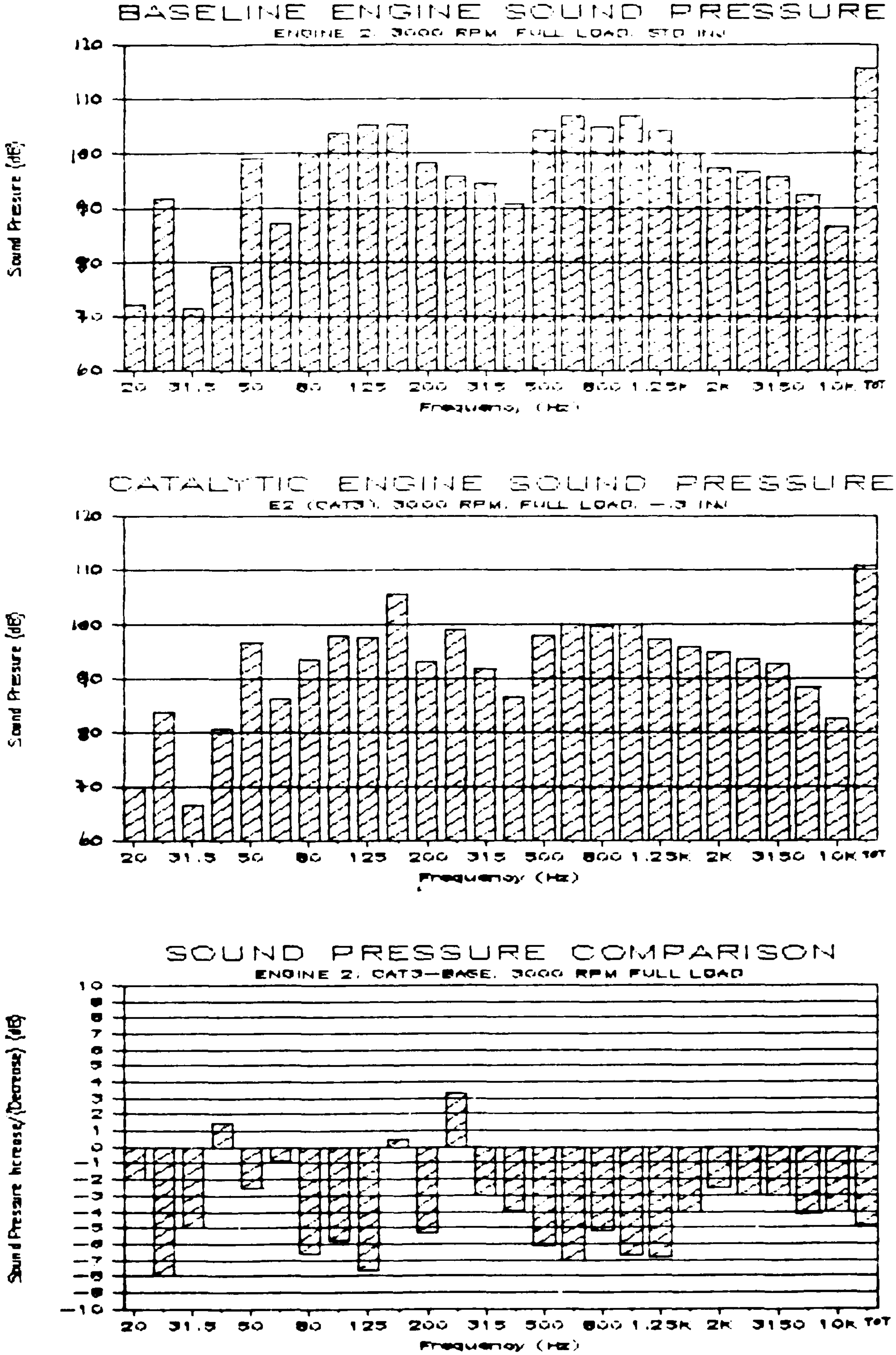

BASELINE ENGINE SOUND PRESSURE
ENGINE 2, 3600 RPM, FULL LOAD
Sound Pressure (dB)
Frequency (Hz)
CATALYTIC ENGINE SOUND PRESSURE
E2 (CAT3), 3600 RPM, FULL LOAD
Sound Pressure (dB)
Frequency (Hz)
SOUND PRESSURE COMPARISON
ENGINE 2: CAT3—BASE, 3600 RPM FULL LOAD
Sound Pressure Increase/(Decrease) (dB)
Frequency (Hz)

FIGURE 13

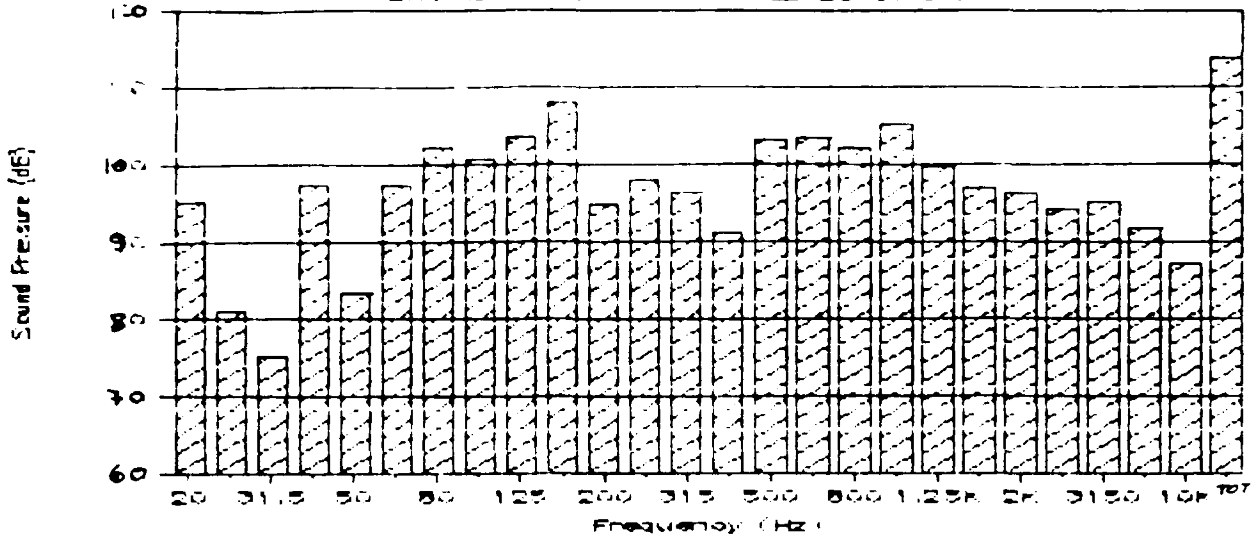


BASELINE ENGINE SOUND PRESSURE
ENGINE 2, 3000 RPM, FULL LOAD, STD INJ
Sound Pressure (dB)
Frequency (Hz)
CATALYTIC ENGINE SOUND PRESSURE
E2 (CAT3), 3000 RPM, FULL LOAD, -3 INJ
Sound Pressure (dB)
Frequency (Hz)
SOUND PRESSURE COMPARISON
ENGINE 2, CAT3-BASE, 3000 RPM FULL LOAD
Sound Pressure Increase/(Decrease) (dB)
Frequency (Hz)

FIGURE 14

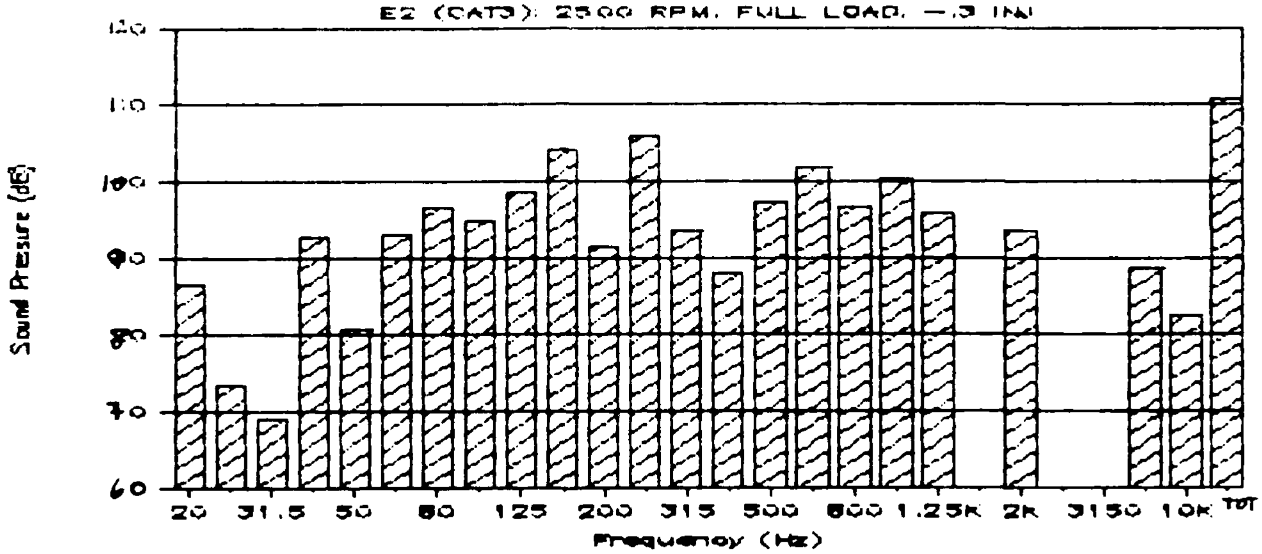
BASELINE ENGINE SOUND PRESSURE

ENGINE 2: 2500 RPM, FULL LOAD, STD INJ



CATALYTIC ENGINE SOUND PRESSURE

E2 (CAT3): 2500 RPM, FULL LOAD, -.3 INJ



SOUND PRESSURE COMPARISON

ENGINE 2: CAT3—BASE: 2500 RPM FULL LOAD

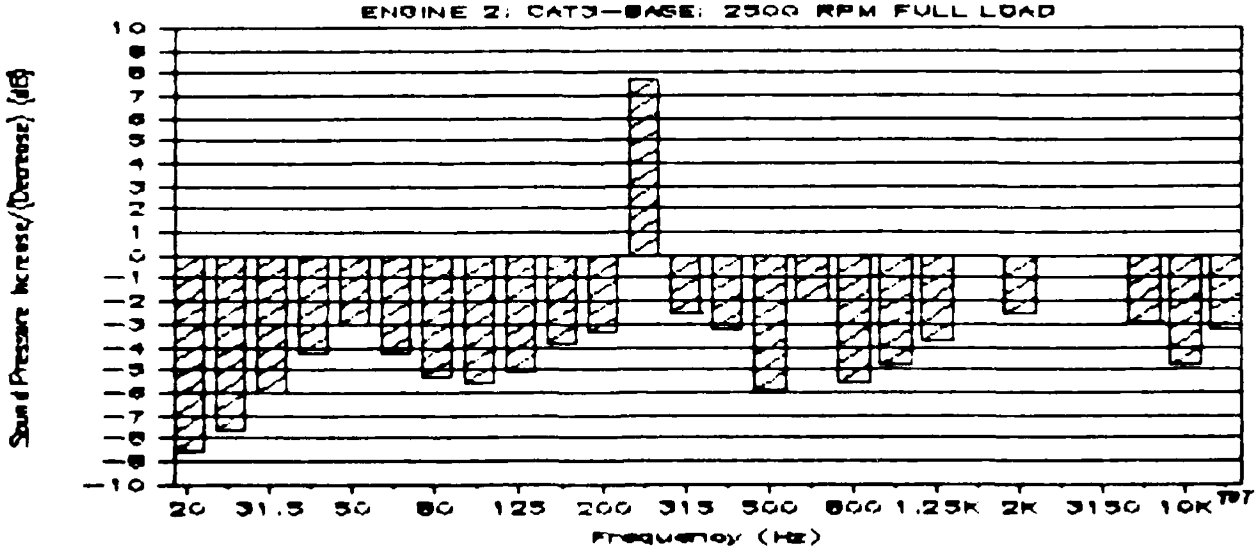
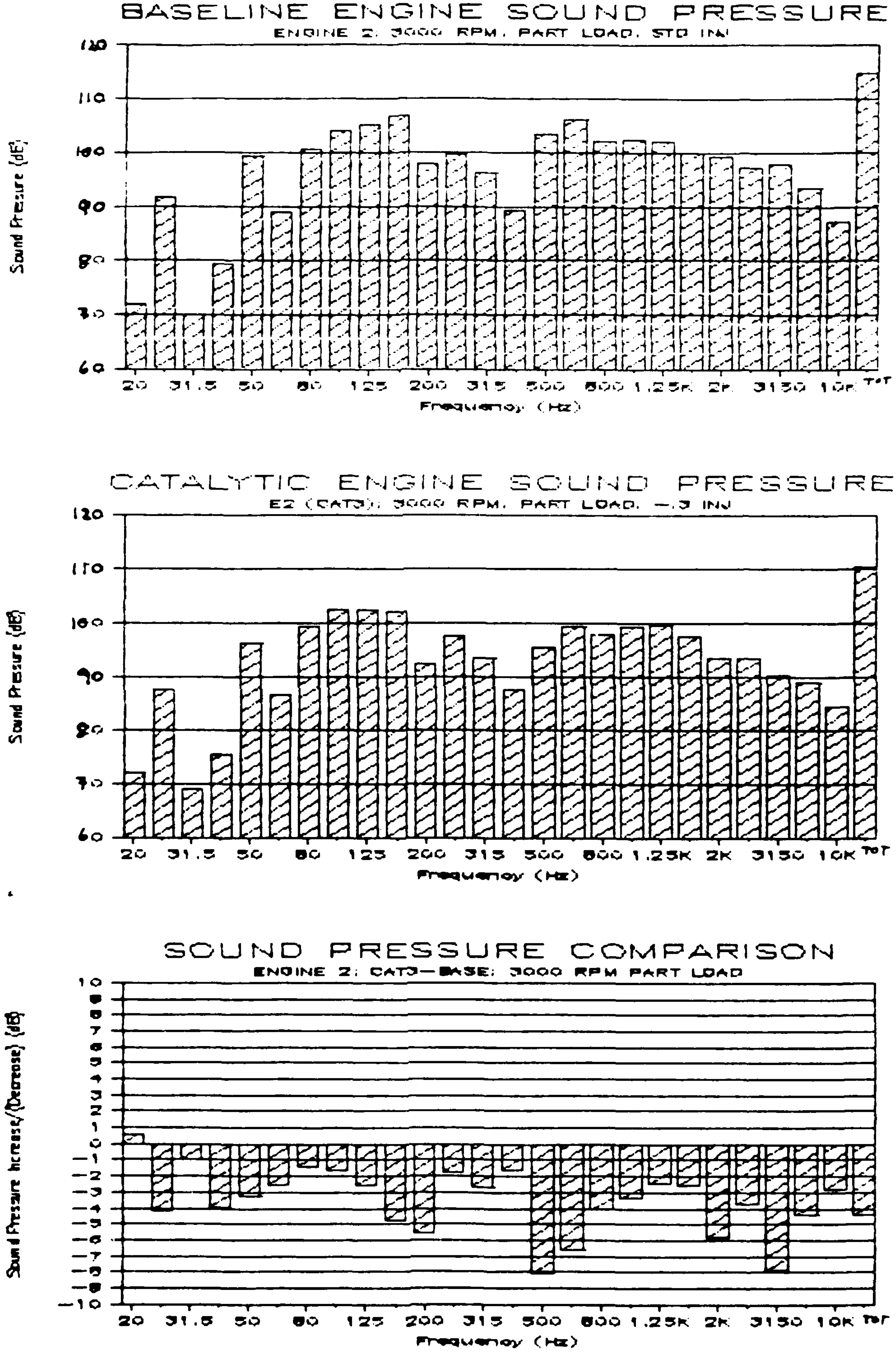


FIGURE 15

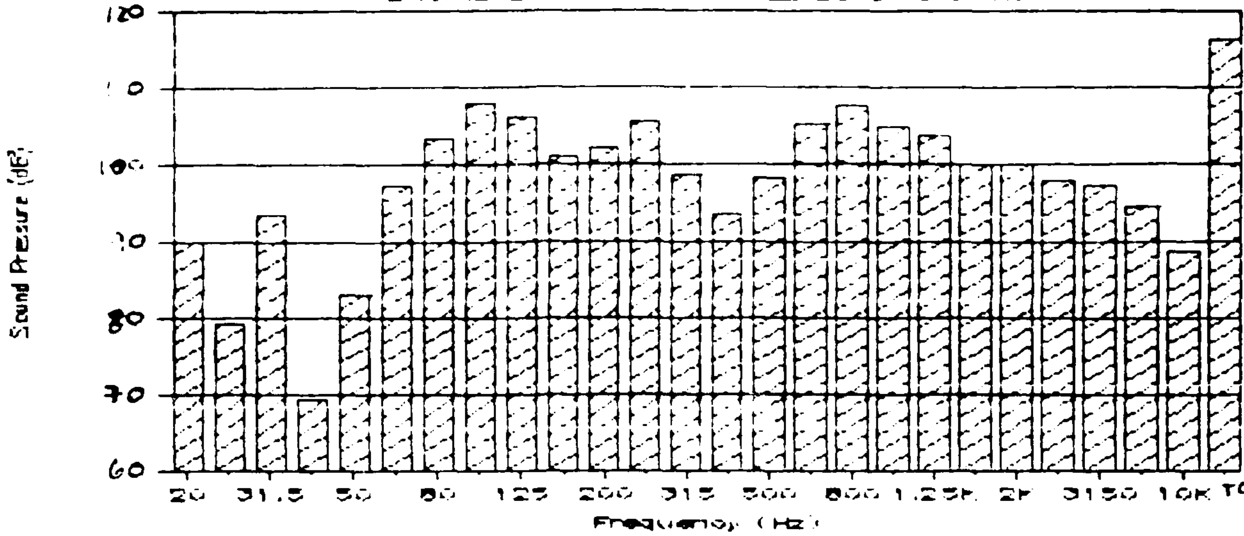


BASELINE ENGINE SOUND PRESSURE
ENGINE 2: 3000 RPM, PART LOAD, STD INJ
Sound Pressure (dB)
Frequency (Hz)
CATALYTIC ENGINE SOUND PRESSURE
E2 (CAT3): 3000 RPM, PART LOAD, -.3 INJ
Sound Pressure (dB)
Frequency (Hz)
SOUND PRESSURE COMPARISON
ENGINE 2: CAT3-BASE: 3000 RPM PART LOAD
Sound Pressure Increase/(Decrease) (dB)
Frequency (Hz)
20 31.5 50 80 125 200 315 500 800 1.25K 2K 3150 10K TOT

FIGURE 1b

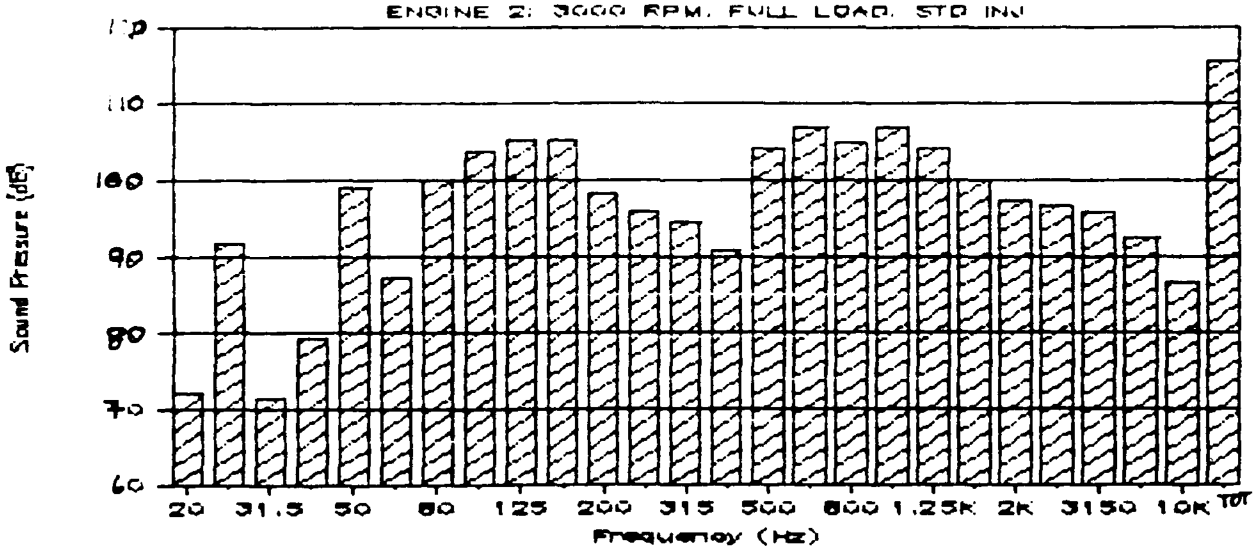
BASELINE ENGINE SOUND PRESSURE

ENGINE 2 3600 RPM, FULL LOAD, STD INJ



BASELINE ENGINE SOUND PRESSURE

ENGINE 2: 3000 RPM, FULL LOAD, STD INJ



BASELINE ENGINE SOUND PRESSURE

ENGINE 2: 2500 RPM, FULL LOAD, STD INJ

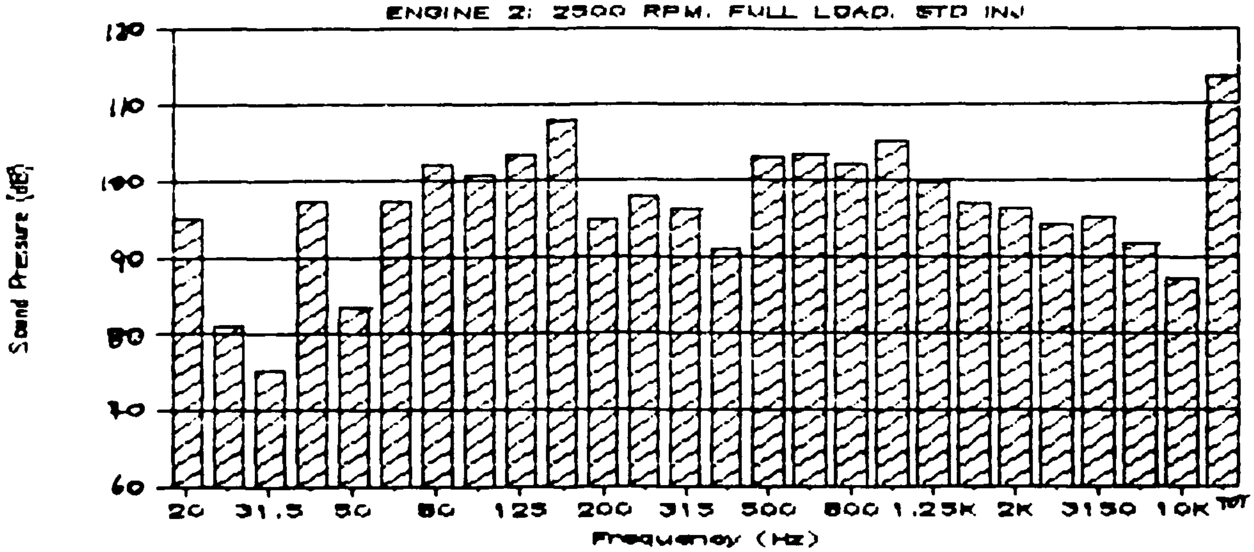
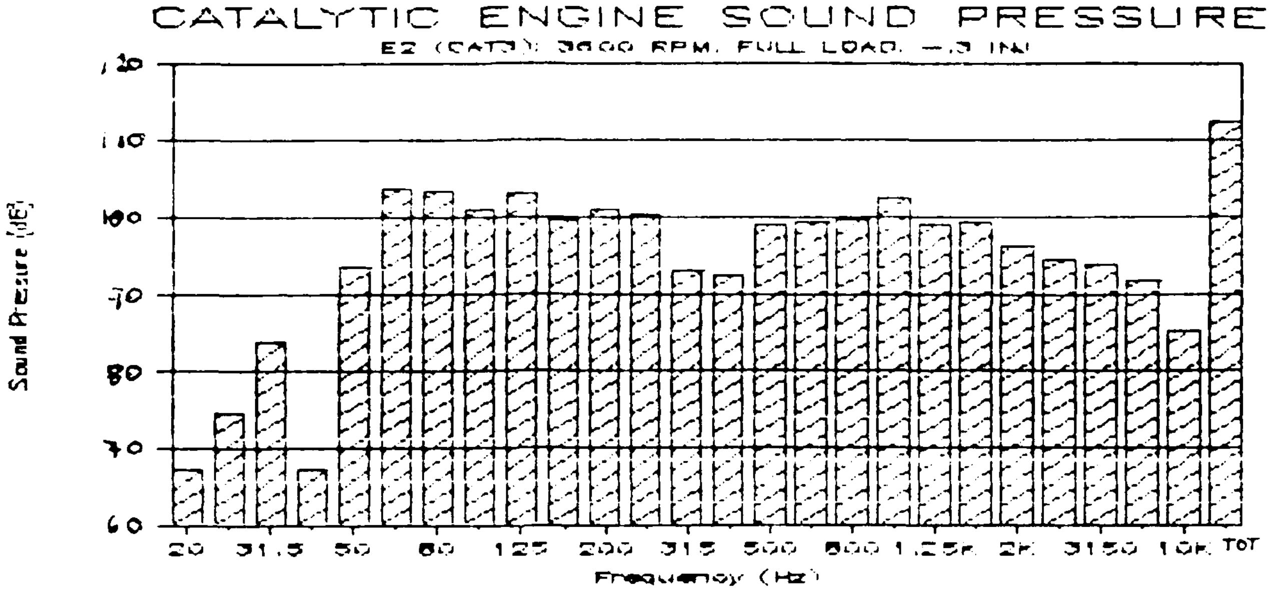
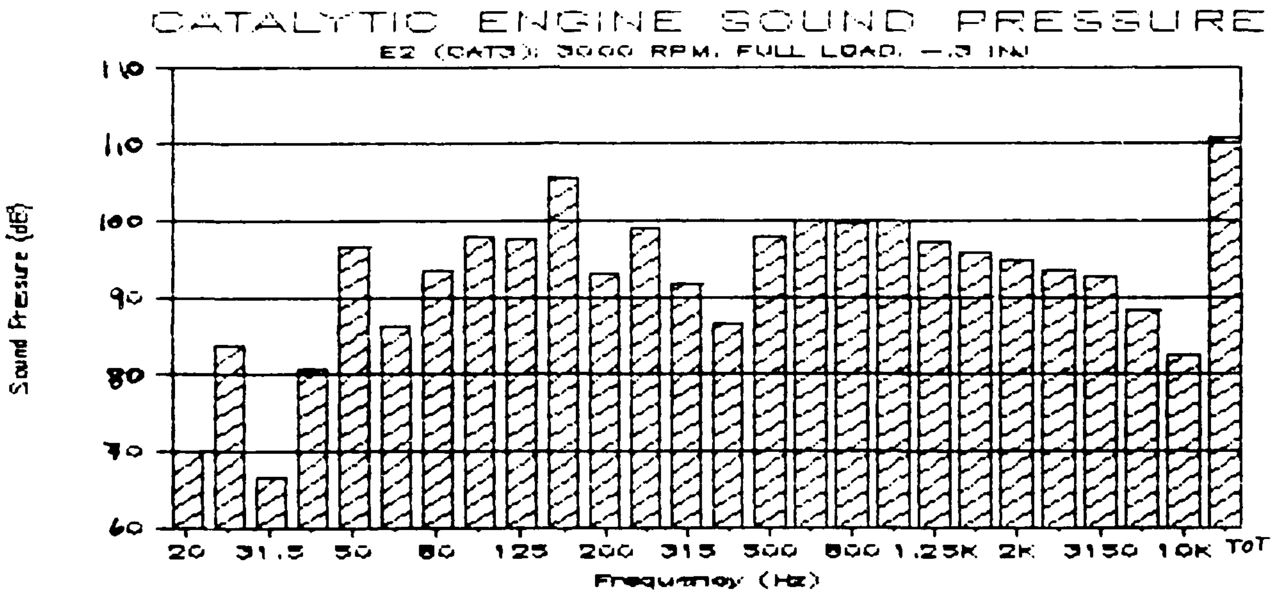
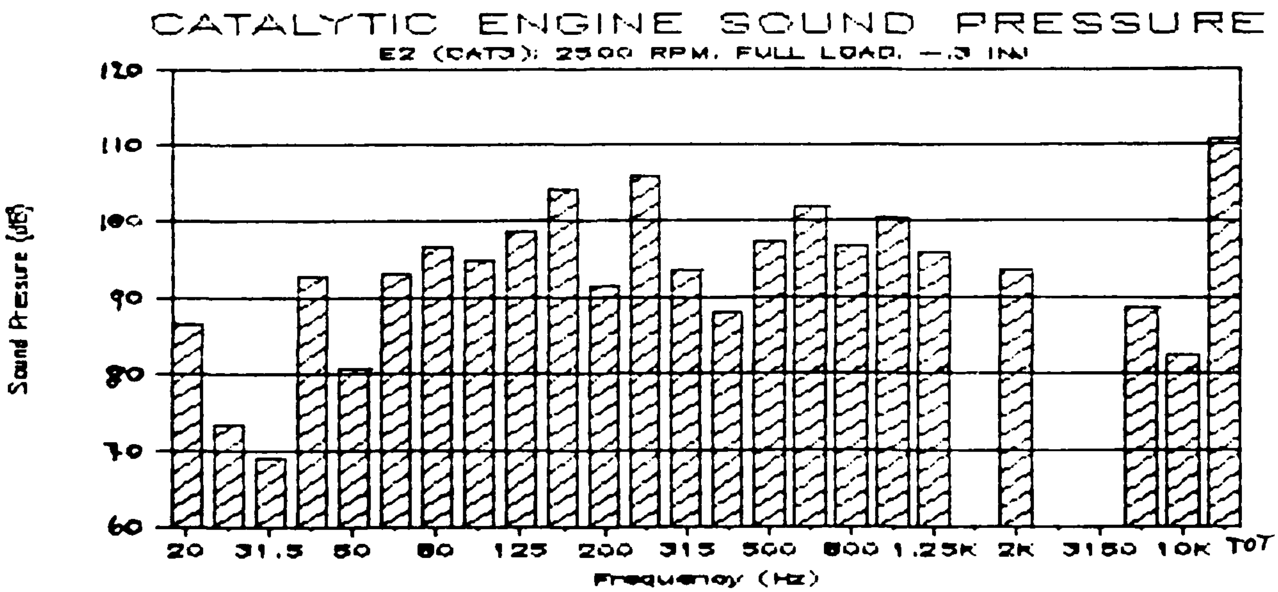
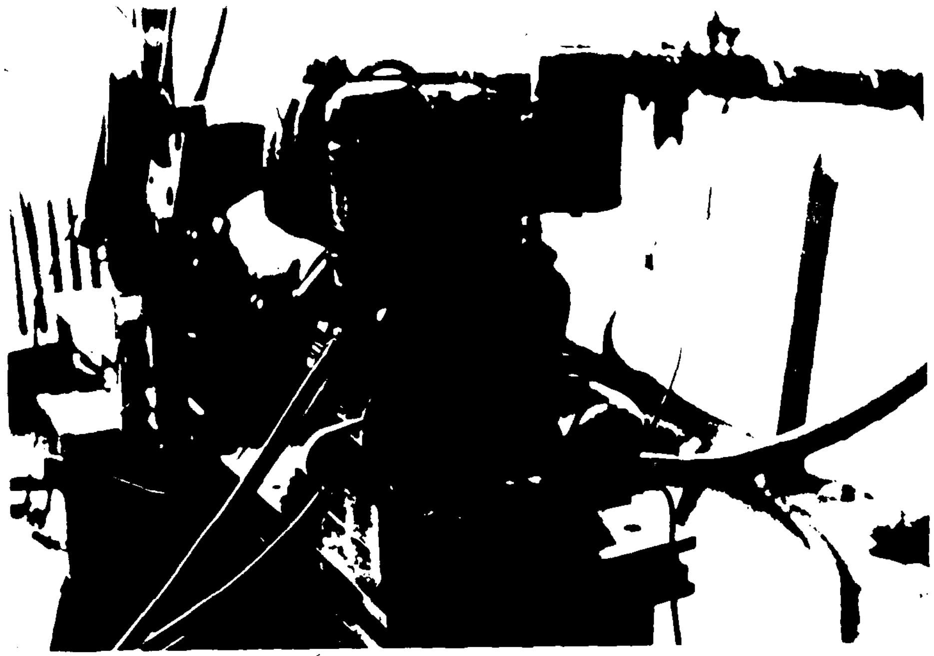


FIGURE 17

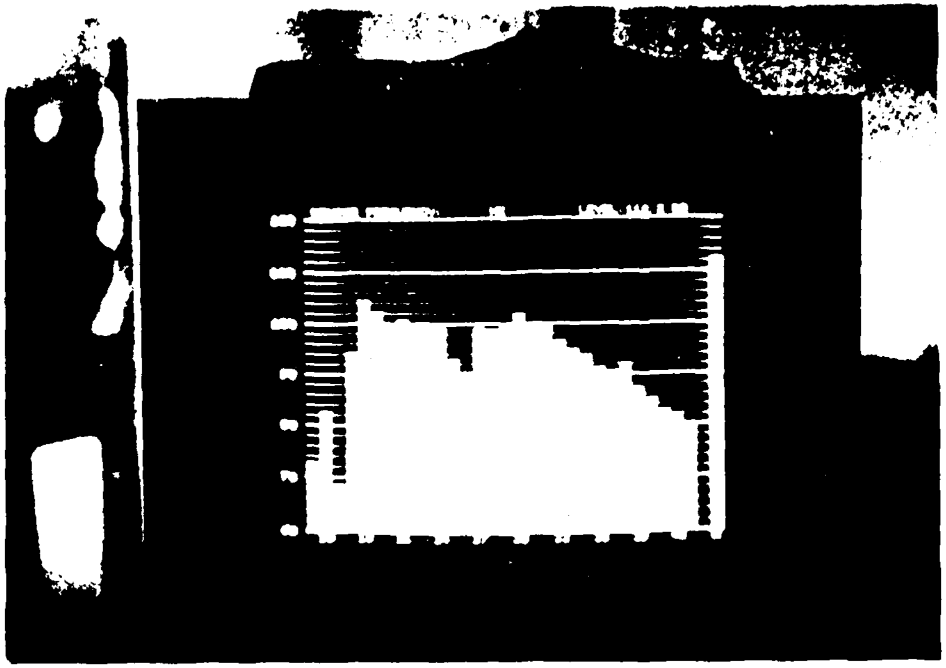

CATALYTIC ENGINE SOUND PRESSURE
E2 (CAT3): 3600 RPM, FULL LOAD, -.3 IN
Sound Pressure (dB)
Frequency (Hz)
20 31.5 50 80 125 200 315 500 800 1.25K 2K 3150 10K TOT


CATALYTIC ENGINE SOUND PRESSURE
E2 (CAT3): 3000 RPM, FULL LOAD, -.3 IN
Sound Pressure (dB)
Frequency (Hz)
20 31.5 50 80 125 200 315 500 800 1.25K 2K 3150 10K TOT

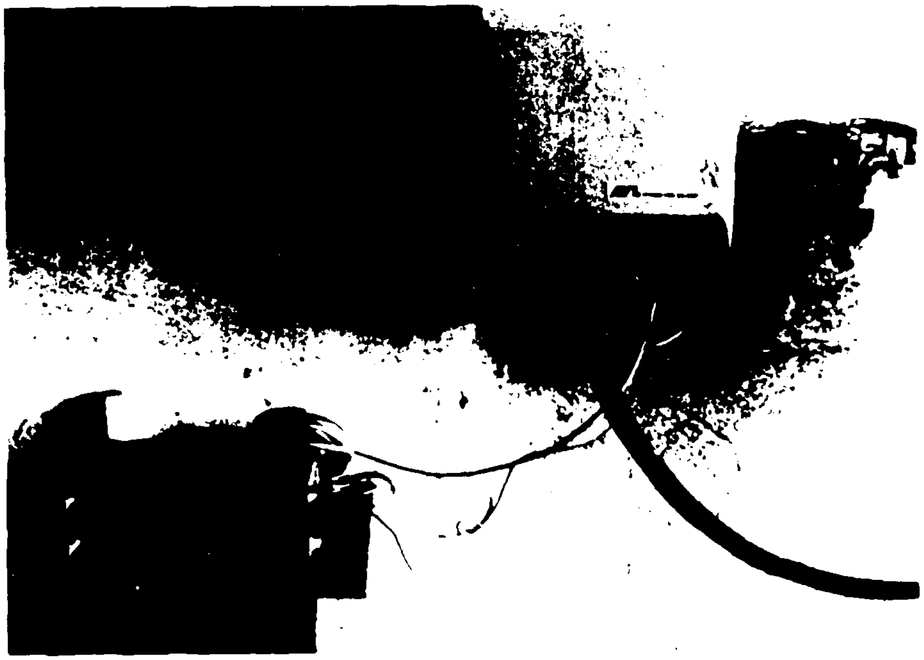

CATALYTIC ENGINE SOUND PRESSURE
E2 (CAT3): 2500 RPM, FULL LOAD, -.3 IN
Sound Pressure (dB)
Frequency (Hz)
20 31.5 50 80 125 200 315 500 800 1.25K 2K 3150 10K TOT

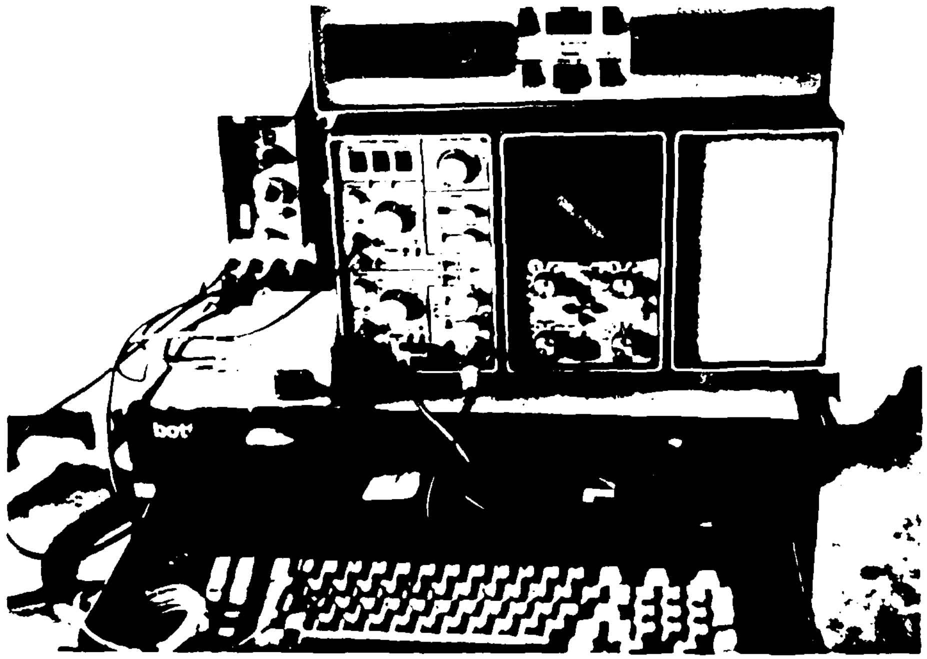


HATZ E673 ENGINE AND DYNAMOMETER



SOUND METER MONITOR (CAT3)





APPENDIX A

PRIOR WORK

Dr. William Pfefferle has a number of U.S. patents related to the use of catalysts to support thermal combustion and the extension of these ideas to a gas turbine configuration. Approximately fifteen years ago Dr. Pfefferle first designed a reciprocating engine in which catalyst structures were placed within the combustion chamber to eliminate engine pollutants (U.S. Patent 3,923,011). In this patent a catalyst grid divides the combustion zone into two regions. Air and fuel enter and exhaust gases pass through this grid during the operation of the engine, the piston being on the opposite side of the grid from the valve mechanisms and fuel injectors. With this configuration not only is the catalyst able to initiate the combustion reaction but the exhaust gases pass through it again during the exhaust stroke and residual pollutants may be converted in a manner analogous to that used in conventional exhaust catalysts. One problem associated with this configuration is the mechanical integrity of the catalyst (a platinum material supported on a ceramic substrate). The presence of a ceramic honeycomb also increases the needed cylinder volume at maximum compression.

A variation of this design was proposed by Haslett [1] and expanded upon by Thring [2] (at Ricardo Engineering) in the late 1970s. In this case the catalyst, in the form of a platinum wire mesh or a sintered porous element, is placed in a prechamber. During fuel injection at top dead center, fuel passes over the catalyst and into the air cell. During the work stroke the fuel/air mixture again passes through the catalytic grid which will provide catalytic assistance for the combustion reaction. This configuration is claimed to reduce or eliminate unburned hydrocarbons in the exhaust and it is pointed out that the ability of the catalyst to support combustion at very high air/fuel ratios permits the engine performance to be adjusted by control of the fuel supply. The catalytically assisted combustion is also stated to permit a wide range of fuel types to be employed with a given engine.

Ricardo Engineering built and ran such an engine, reporting that a platinum catalyst mesh permits operation of a diesel engine at lower compression ratios. When the platinum mesh catalyst was replaced by stainless steel mesh, the engine would not run. Nitrogen oxide emissions were demonstrated to be lower than even the stratified charge engine. In addition, their tests demonstrated "better fuel economy (at low engine loads) than conventional gasoline engines coupled with lower hydrocarbon emissions than either gasoline or diesel engines". The engine performed equally well with diesel or alcohol as the fuel. Noise was also reported to be lower.

Interesting as these results are, fuel economy was not good at high speeds and catalyst durability was a problem. It is

apparent that in the Ricardo engine the catalyst is subject to very high full load flame temperatures leading to catalyst deterioration. Lowered fuel economy at high speeds was ascribed to the catalyst gauze physically obstructing gas flow within the cylinder. The work appears to have been discontinued.

Experimental data on catalytically assisted diesel combustion were reported in 1980 by Sapienza et al [3] of Brookhaven National Laboratories. These results were preliminary and were obtained using a standard Waukesha CFR engine in which the piston crown had been coated with platinum. The durability of this coating was low but it was reported that the presence of the catalyst reduced the soot emissions from the engine by about a 45% as compared to the same engine with the uncoated piston. A General Motors study was unable to reproduce the Brookhaven results.

We are aware of two other references to catalytic engines, the first consisting of translated Russian articles referring to catalytic engine coatings and the second being an abstract of work done by a Chinese (PRC) researcher. Descriptions of the former work claim a reduction in varnish build-up on the engine, and may involve catalytic oxidation but do not appear to us to have any catalytic ignition component. The Chinese abstract reports catalytically coating the interior of a diesel engine and getting positive results including efficiency improvements and reduced emissions. We cannot form any conclusions on the abstract alone and we are attempting to get an English translation of the article itself.

Separate experimental work with a catalytically-assisted compression-ignition engine was reported by Beyerlein & Wojcicki [4] at the Spring 1986 Western States Combustion Institute meeting. This work again involved a catalyst in the prechamber. We have formed a working relationship with Beyerlein, and we consider their his work useful although different from our technology.

1. Haslett, R., U.S. Patent 4,092,967, June 1978.
2. Thring, R., Platinum Metals Review, 24, (1980) p. 126.
3. Sapienza, R., Butcher, T.,Krishna, C. and Gaffney, J., Proceedings 4th Workshop on Catalytic Combustion, EPA-600/9-80-035 (1980) p. 380.
4. Beyerlein, S. and Wojcicki, S., "Catalytically Assisted Compression Ignition of Ultra-Lean Mixtures", Spring 1986 Meeting of the Canadian and Western States Sections of the Combustion Institute.

REFERENCES

[1] B.J. Challen, "Techniques for Engine Noise Control", Engine Noise, Hickling, R. and Kamal, M., editors, Plenum Press, 1982.

[2] H. Ricardo, "Combustion in Diesel Systems", Proceedings of I.A.E. (London), March 1936.

[3] C.F. Taylor, The Internal Combustion Engine, Vol 2, MIT Press, Cambridge, Massachusetts (1982).

[4] Hickling, R., Chen, F.H.K., and Feldmaier, D.A., Pressure Pulsations in Engine Cylinders, Engine Noise, Hickling, R. and Kamal, M., editors, Plenum Press, 1982.

[5] R.A. Dykstra, "I.C. Engines and Noise", Noise Control in I.C. Engines, D.E. Baxa, editor, J. Wiley, 1982.

[6] D. Anderton, E. C. Grover, N. Lalor, and T. Priede, "Origins of Reciprocating Engine Noise", ASME Paper 70-WA/DGP-3, 1970

[7] T. Priede, Noise of Engines, SAE paper 750795, 1975.

[8] J. W. Slack and R. H. Lyon, "Piston Slap", Engine Noise, R. Hickling and M.M. Kamal Eds. Plenum Press, p. 39, 1982.

[9] M.F. Russell and R. Haworth, "Combustion Noise from High Speed Direct Injection Diesel Engines", SAE paper 850973, 1985.

[10] V. Tung and M. Crocker, "Diesel Engine Noise and Relationship to Cylinder Pressure", SAE paper 820237, 1982.

[11] D. Anderton, "relation Between Combustion System and Engine Noise", SAE paper 790270, 1979.

[12] W. Strahle, "Combustion Randomness and Diesel Engine Noise: Theory and Initial Experiments", Combustion and Flame, 28, p.279-290, 1977.

[13] W. Strahle, "Turbelent Combustion and Diesel Engine Noise", Seventeenth Symposium (Intl) on Combustion, The Combustion Institute, p. 337 - 346, 1978.

[14] C. Wagner, Chem. Technol., (Berlin), 18, 28, 1945.

[15] W.C. Pfefferle, "The Catalytic Combustor: An Approach to Cleaner Combustion", J. Energy, 2, p. 142 - 146, 1978.

[16] D.N. Anderson, R.R. Tacina, and T.S. Mroz, "Performance of a Catalytic Reactor at Simulated Gas Turbine Conditions", NASA Technical Memo X-71747, June 1975.

[17] B.E. Enga, "Catalytic Combustion in Actual Engines", Proc. 3rd International Workshop on Catalytic Combustion, EPA report

600/7-79-038, pp 491 - 512, 1979.

[18] R.J. Catollica and R.W. Schefer, "Effect of Surface Chemistry on the Development of [OH] in a Combustion Boundary Layer", 19th (Intl) Symposium on Combustion, The Combustion Institute, pp. 311-318, 1982.

[19] Pfefferle, W.C. and Pfefferle, L.D., "Catalytically Stabilized Combustion", Progress in Energy and Combustion Science, Vol 12, pp25-41, 1986.

[20] S. Muranaka, Y. Takagi and I Tokuhei, "Factors Limiting Improvement in Thermal Efficiency of a S.I. Engine at High Compression Ratio", SAE paper 870548, 1987.

ACKNOWLEDGEMENTS

We wish to acknowledge the assistance of a number of parties in the successful completion of this study. Special thanks are due to Dragos Ionescu, Dorin Morar, Mihai Soiman, and Richard Syson, who provided invaluable support in the manufacture of the prototypes used and in the engine tests themselves. The fact that much of this was accomplished immediately before and subsequent to their employer's Chapter XI filing is a credit to the morale, pride and determination of this group of people. We appreciate their support in times of high personal uncertainty.

We also thank Dr. Robert Apfel of Yale University for his advice in designing and interpreting the noise study. His doctoral student Christy Smith also provided important insights. Dr. Lisa Pfefferle's assistance in combustion modeling and data interpretation have added to the depth of our understanding of the results. Steve Beyerlein, a doctoral student at Washington State University, has also been very helpful in our research efforts.

Finally, we thank the Belvoir R, D and E Center for its financial support of this promising technology, and we thank our project officer, Art Kinser, whose pragmatic approach and support helped us surmount the hurdle we faced when our engine testing subcontractor entered Chapter XI proceedings.

END
DATE
FILMED
DEC.
1987